Assessment of the use of green and reflective roofing on the Urban Heat Island in London

by

Kevin Katigbak

The Bartlett School of Graduate Studies

University College London

A Dissertation submitted in part fulfilment of the
degree of Master of Science Built Environment:
Environmental Design and Engineering

University of London

150905

Abstract

High-density urban development, highly absorptive surfaces and absence of green space have had a negative impact on localized microclimate. The increase of surface temperature due to these factors exhibits consequential increase energy consumption and implies the need for increased climate conditioning.

The model demonstrates the impact of typical urban composition on the surrounding environment and suggests the urban fabric itself causes the major weight of UHI. Where variables, such as roof types, are introduced, the patterns in surface temperature suggest a strong correlation between roof surface and energy consumption.

A hypothetical city block located in a densely developed urban area has been modeled using TAS EDSL as the modeling tool, in an attempt to assert the effects of green and reflective roofing on the surface and surrounding temperatures of the model. Additionally the effect of these technologies has on the overall building energy consumption has been examined.

Key findings concur with previous research conducted in the field including:

- The modeled green roof shows a reduction in surface temperatures compared to the base model
- Using materials with various increased reflectivity from the base model show reduction in surface temperatures and surrounding temperatures as compared to the base model.
- Both the use of green roofing and reflective roofing materials have a positive affect on the reduction of overall energy consumption for a cooling season

Through the use of green roofing or highly reflective roofing materials, the effects of UHI and global warming may be reduced.

Contents

List of figures

1.0 Introduction

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"

- Sustainable development as defined by the 1987 World Conference on Environment.

In August 2003 London temperatures achieved an all time high of 38.1 °C. During that same period, a heat wave across Europe resulted in forest fires, drought, and the loss of thousands of elderly and ailing lives. This dramatic increase in surface temperature also provoked an increase in energy use as cities attempted to cope with the heat through air conditioning and other electric cooling methods[1].

Temperatures are often significantly higher in cities than in rural settings, making these seasonal changes particularly dangerous for today's urban populations. Known as the Urban Heat Island Effect[2], (UHI hereafter) this phenomenon suggests that the dark surfaces found in high concentrations in developed areas – in the form of paved roads, dark surfaces, and concurrently, limited green space – can significantly intensify summer temperatures. Dense clustering of buildings and anthropogenic heat gain further magnify this heat gain, creating uncomfortably warm temperatures within urban environments.

In addition to comfort levels, the occurrence of UHI also has a definite and measurable influence on energy consumption. In the summer time, instances of internal environmental conditioning increases. As artificial conditioning increases, so too does fossil fuel usage and emissions, with known consequences on global warming and climate change. The problem of UHI is therefore a local challenge with global implications, and requires innovative solutions for its mitigation.

The Environmental Protection Agency (USA) has cited the use of green or vegetative roofs as a possible way to mitigate the effects of UHI. The use of high performance reflective roofing has also been found to be effective. Predicting the result of certain material on the surrounding environment can be a difficult endeavor, however, considering the many variables of urban development, location and climate. In terms of sustainability, the use of high performance roofing, such as green and reflective roof systems, generally produce desirable results.

[1] CNN, 2003, Europe swelters under heatwave, http://www.cnn.com/2003/WORLD/europe/08/06/heatwave

[2] Akbari, Hashem, 2000, Urban Heat Island Group, http://eetd.lbl.gov/HeatIsland/.

This thesis uses modeling and simulation to estimate the effects of green and reflective roofing on the temperatures found in UHI. It uses the city of London as an example, focusing on two neighborhoods in particular. The main objectives of this body of work are to:

assess the viability, or otherwise, of green roofing systems, for London's climate evaluate the use of green roofing and reflective roofing for reducing:

1. UHI effect
2. Energy consumption for cooling
3. Carbon emission

It is hypothesized that reducing the effects of UHI will thereby reduce the associated consequences of it (energy use and emissions) and may therefore have a positive effect on climate change. By reducing the UHI, it is possible to reduce carbon emissions from buildings by reducing the energy required to cool them. The effectiveness of green and reflective roofing is tested in this context to evaluate if this hypothesis is true for the case of London, England.

2.0 Climate Change

The term climate change refers to the long term changes in the climate, generally as a result of many factors including by natural means. Evidence indicates that the global temperature has increased by 0.5°C within the last century, however, not necessarily due to human activity. Historically there have been episodes of dramatic increase and decrease in global surface temperatures due to natural occurrences. These natural occurrences (i.e. volcano eruptions, forest fires etc) can cause quite large variations in temperature. It should be noted that the separation of natural climatic variation from human generated climatic variation is extremely complicated, nonetheless, there is noteworthy scientific evidence that indicates the current trends of increasing global surface temperature are a result of human activity[3].

Figure 1 illustrates the global temperature trends as noted by the Intergovernmental Panel on Climate Change. The illustration indicates that continental Europe has seen an increase in temperature of between 0.4 and 1.0. Although human activity is slightly harder to predict, it is almost certain that increasing atmospheric concentrations of carbon dioxide and other greenhouse gases will cause global surface climate to be warmer. The Intergovernmental Panel on Climate Change (IPCC) suggests an increase of 3 C through to the end of the 21st century.

Climate change and global warming may be directly affected by the occurrence of UHI. The reduction of occurrence of UHI is beneficial to reduce the effects of global warming by reducing carbon emissions and energy consumption.

[3] Mc Mullan, 2002, Environmental Science in Building, Palgrave, London.

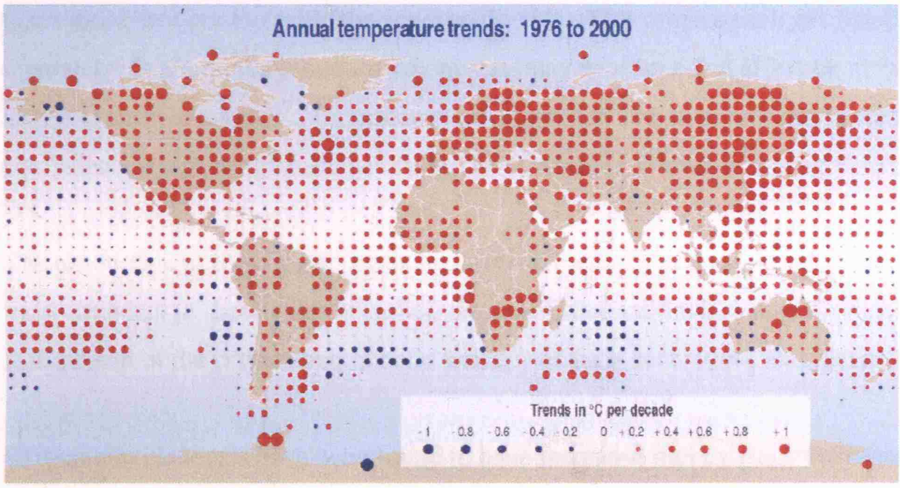


Figure 1 Annual Temperature Trends: 1976 to 2000. (Source: IPPC)

2.1 The Causes of Global Warming

The emission of "greenhouse" gases is believed to be the primary source of climate change and global warming. The term greenhouse gas refers to a gas that contributes to the greenhouse effect. This type of gas absorbs radiation at specific wavelengths within the spectrum of radiation (infrared radiation) the gas in turn emits infrared radiation from a level where the temperature is colder than the surface. The result of is a local trapping of some of the absorbed energy and a tendency to warm the planetary surface[4]. The radiation from the sun is primarily short wave and the radiation from the earth is long wave radiation. As the atmosphere becomes increasingly absorbent to infrared radiation due to the presence of greenhouse gases, both natural and anthropogenic, heat gets trapped. This trapping of heat is known as the green house effect[5].

The 5 major emissions of concern are: carbon dioxide, methane, ozone, nitrous oxide and Chlorofluorocarbons. The presence of these gases in the atmosphere, in abundance, results in radiative forcing which is the change in the balance between radiation coming into the atmosphere and radiation going out. A positive radiative forcing tends on average to warm the surface of the Earth, and negative forcing tends on average to cool the surface[6].

The physical ability of each type of gas to absorb heat differs greatly and relates to the extent to which the gas affects global warming. For instance, nitrous oxide has the ability to absorb 270

[4] Climate change: a glossary by the Intergovernmental Panel on Climate Change, 1995.
[5] Barry, R.G, 2003, Atmosphere Weather and Climate, Routledge, Francis Taylor Group, November.
[6] Intergovernmental Panel on Climate Change

times more heat per molecule than carbon dioxide. This implies each gas must be monitored separately, as a minimal reduction of one gas, may have an equal effect on global warming as a large decrease of another[7]. Greenhouse gas emissions shown in millions of metric tons of carbon equivalents which weigh each gas by its GWP value, or Global Warming Potential[8]

The production of these gases, again, occur both naturally and as a result of human activity. The most abundant of these gases is carbon dioxide. Carbon dioxide is also the most easily controlled. It is a result of the combustion of solid waste, and fuels such as oil, natural gas, coal and wood.

Carbon dioxide levels have been found to have increased rapidly since the Industrial Revolution. Nearly 80% of the total increase since the early 1700's has occurred in the 20th Century.[9]

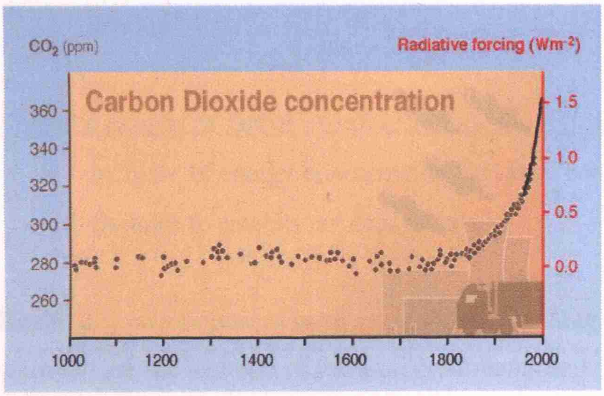
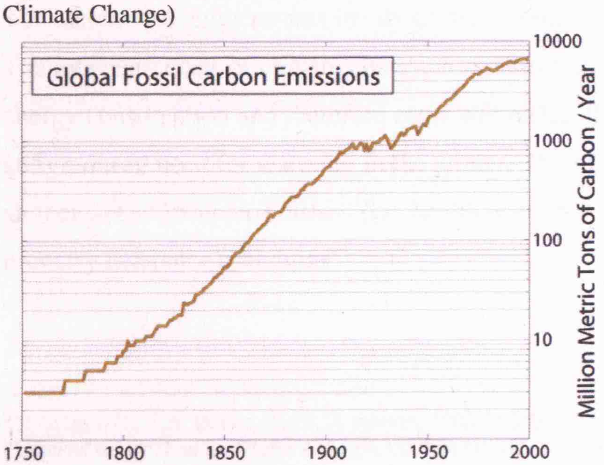


Figure 2 Carbon dioxide levels since the industrial revolution. (source: Intergovernmental Panel on Climate Change)



[7] Defra, 2005, environmental protection, http://www.defra.gov.uk/environment/climatechange/01.htm#details
[8] GREENHOUSE GASES AND GLOBAL WARMING POTENTIAL VALUES EXCERPT FROM THE *INVENTORY OF U.S. GREENHOUSE EMISSIONS AND SINKS: 1990-2000*
[9] Turekian, C. Vaughn, 2001, An analysis of some key questions: climate change.

Figure 3 Global carbon emissions from fossil fuels: industrial revolution to present[10]. (source: U.S. Department of Energy)

2.2 Effects of Global Warming

There are both positive and negative effects of global warming, however only issues relevant to this report will be discussed[11].

Positive aspects of global warming include the following:

- Northern climates would arguably experience more desirable weather, in terms of health; Cold related stress would certainly reduce.
- As a result of increased temperature, there would be a decrease of energy use for space heating

Negative aspects of global warming include the following:

- Increase of energy consumption for space cooling
- Damage to established ecosystems.

Health is a major concern in terms of global warming. Some direct and obvious effects of global warming are the increase of respiratory ailments and disease[12].

The increase of temperatures in city centres would amplify the effects of air pollution[13]
The monetary costs of climate change correlates with all the aforementioned issues. Increase in energy consumption and therefore costs will reflect the increase need for cooling in the simmer ands reduced need for warming in the winter. Rapid climate change will consequently result in an increase of insurance claims (i.e. health insurance premiums to rise) and the increase of property insurance premiums[14].

---

[10] Marland, G., T.A. Boden, and R. J. Andres. 2003. "Global, Regional, and National CO2 Emissions." In *Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center*, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A

[11] For additional information on global warming consult Global Warming the Complete Briefing, 1997, John T Houghton

[12] World Health Organisation

[13] World Health Organisation

[14] Intergovernmental Panel on Climate Change

As the issue of global warming first gained prominence on an international platform, approaches to control the phenomenon to some extent have become internationally significant. The following section briefly discusses these approaches and the relevant policies which may affect UHI and its mitigation efforts.

2.3 Context of global policy in regards to climate change

The current policy context for climate change was born at the 1992 Earth Summit in Rio de Janeiro. This summit led to the signing of the UN Framework Convention on Climate Change – and eventually the drafting of the Kyoto Protocol in 1997. These protocols form the current agenda regarding the reduction of carbon emissions as a global effort.

The Kyoto protocol (1997) provided the first clear action to be taken in the reduction of greenhouse gasses. The document, which sought to reduce greenhouse emissions by providing ambitious guidelines for some 38 developed countries, has not been entirely ratified due to hesitance from some major players[15].

The quandary surrounding the Kyoto protocol is the absence of provisions regarding economic recovery subsequent to ratification. This is the primary reason countries such as the United States have not yet fully supported the protocol. A report by the American Energy Information Administration (AEI) suggests that implementing Kyoto would result in the drastic rise of energy prices high in greenhouse emissions. This increase in energy would lead to increased energy taxes. It would also hit the coal industry (or any energy source high in green house gas emissions) dramatically, accounting for an increase in unemployment, and the eventual reduction of GNP. Finally, public spending which has been a major factor in economic recovery in the past would be reduced. Despite the moral and ethical intentions of Kyoto regarding global warming, without clear provision to mitigate economic effects, it will not appeal, nor be implemented by heavily industrialized countries[16]

[15] Kyoto Protocol, 1997
[16] American Information Administration

2.4 UK Commitment to Emissions Reduction

Although hearings such as the Earth Summit take place within an international platform, they are strictly guidelines to promote a sustainable future. They still require the governance of individual countries. The UK has adopted several policies, codes of practice and regulations to further improve reduction of carbon emissions in the UK.

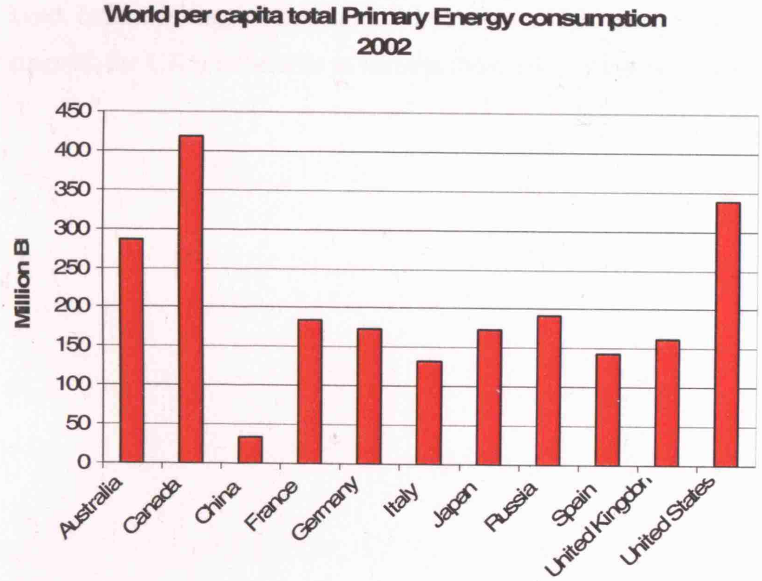


Figure 4 World per capita total primary energy consumption million Btu 2002(Source: IEA[17])

In the UK many policies and regulations have already been adopted in compliance with Kyoto, as well as the UK's own agenda.

Action taken in the UK throughout the 1990s has significantly reduced greenhouse gas emissions. The Government and the devolved administrations are continuing this positive approach with a substantial programme of integrated policies and measures[18].

The Energy White Paper set energy efficiency at the heart of UK energy policy, identifying improved energy efficiency as the most cost-effective way to meet all of our energy policy goals. Using less energy can reduce carbon emissions, enhance the security of our energy supplies,

---

[17] International Energy Annual, 2002

[18] Defra, 2005, http://www.defra.gov.uk/environment/climatechange/02.htm

improve the competitiveness of UK businesses and reduce fuel poverty[19]. The White Paper declared the Government's goal to reduce the UK's carbon emissions by 60% around 2050. By 2010, the UK expects to reduce carbon emissions by 20% below 1990 levels[20].

Presently the UK has been able to reduce the production of greenhouse gas emissions by 14.5 percent within the span of 9 years (between 1990 and 1999). This success has occurred mainly through shifting from the use of coal as primary fuel to the increase of natural gas. On the other hand, estimates suggest that the UK increased CO_2 emissions by 2% in 2002[21]. Even on this account, the UK will be able to surpass the original figure detailed in the protocol by 2012[22].

---

[19] Energy White Paper, 2003, UK, February.
[20] *ibid*
[21] OECD Environmental Performance Reviews, 2004, Organisation for Economic Co-operation and Development, January
[22] Defra

3.0 Urban Heat Island

The economic prosperity, social benefits and cultural stimulation of large cities has, and will continue to have, a major attraction for suburban populations moving into urban centres. Now more than ever, inhabitants of smaller towns and villages find themselves migrating to major cities. The continuous influx of population has given opportunity for cities to develop at phenomenal rates, but has also come at a cost. The urban landscape sprawls with paved roads, concrete buildings and highly dense populations. These instances amplify the occurrence of the urban heat island effect, whereby urban areas display increased temperatures due to human activity.

The term urban heat island refers to the phenomenon of localized pockets of increased temperature within the urban environment. It describes the ability of the urban fabric to alter the state of the microclimate[23].

The growth of cities has modified the natural landscape, altering the way in which it responds to the environment. This type of development leads to the UHI, based on urban development resulting in diminished green spaces and the increase of dark surfaces in the city in the form of asphalt paving and dark coloured roofs. The increase of asphalt and concrete roads, buildings and other development associated with large cities, will absorb the suns heat causing surface temperatures to increase, which, results in an increase of overall ambient temperatures[24] . London is a dense city with a population of seven and a half million inhabitants.

As a large and dense urban environment, London is naturally susceptible to the effects of UHI. Both the compact land development and high population tend to maximise the anthropogenic heat gains in central London's urban footprint. Land uses within the greater London area show a high amount of green space relative to other land development such as roads, buildings, and water, which may mitigate UHI effects. The major concentrations of green spaces are found on the outskirts of London, as well as in the form of parks within the centre. Still there are many islands of densely built areas found throughout the city.

---

[23] Bass, B, et al, 2001, Reducing the urban heat island and its associated problems, *The Green Roof Infrastructure*, vol3, no1,.
[24] EPA, environmental protection agency

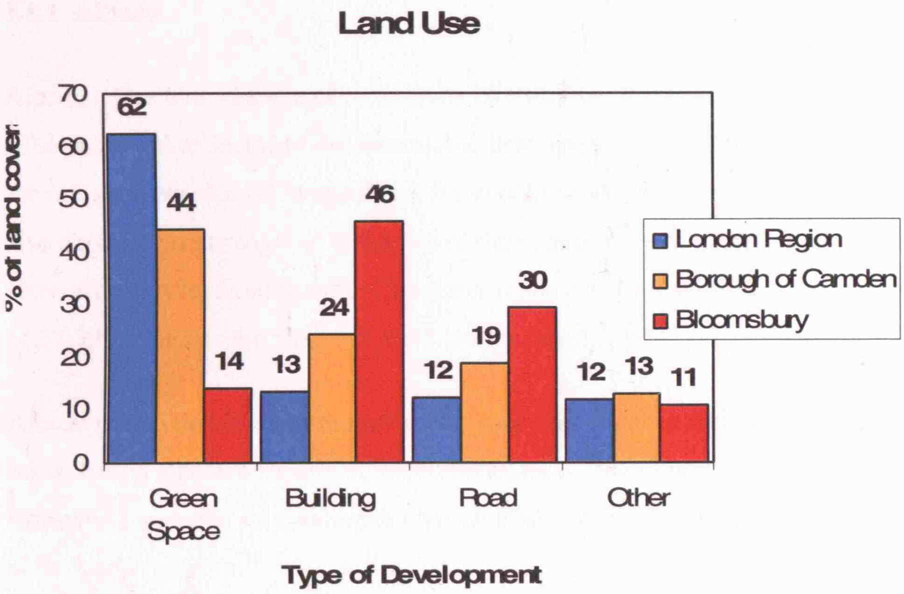


Figure 5: Land use in the Greater London Region, Borough of Camden, and Bloomsbury Neighbourhood (source: ODPM generalised land use database)[25]*[*]

Figure 5 illustrates the levels of both built and green space in the Greater London Area. When considering the London region, the percentage of land that is green space is 62%, a relatively high amount. When observing the same proportion of land use within a defined neighbourhoods in central London (Camden and Bloomsbury) the ratio of green space to building and road development decreases significantly to 44% and 14% respectively.

3.1 Influences on urban heat island

UHI is a result of several factors including; anthropogenic heat released from fuel combustion and people, decrease of vegetation, less wind cooling through convection due to urban configurations, and solar heat stored in urban fabric given the diurnal effect of developed areas. UHI occurs when former green areas are replaced with developed sites.

---

[25] ODPM, 2004, Generalised Land Use Database: England

[*] The definition green space includes gardens as well as built parks and natural woods/heath land, Building includes both domestic and non domestic building, Other includes water, paths, rail, and unspecified land use

3.1.1 Albedo

Albedo refers to a measure of reflectivity of a surface. It is the ratio of electromagnetic radiation (EM radiation) reflected to the amount incident upon it. This ratio depends on the frequency of the radiation considered: unqualified, it refers to an average across the spectrum of visible light. It also depends on the angle of incidence of the radiation: unqualified, normal incidence. Fresh snow albedo is high: up to 90%. The ocean surface has a low albedo. Earth has an average albedo of 37-39% whereas the albedo of the Moon is about 12%[26].

Albedo is also described as normal reflectance. For instance a highly reflective surface, such as snow, has an albedo of nearly 1, which indicates it reflects nearly 100% of the sun's rays. However, a material such as asphalt has an albedo of 0.07, which indicates it reflects a mere 7% of the sun's radiation[27]

Replacement of high-albedo natural ground with low-albedo asphalt and building surfaces also has an effect, though natural forest has a low albedo. Darker surfaces tend to absorb solar energy increasing heat concentration, while lighter reflective surfaces tend to deflect solar energy, reducing surface temperatures. As mentioned, the development of cities is characterized by the increase of built structure and reduction of green space. In some major urban areas as much as 27% of the land cover is roof surface, and 30% is paved surfaces [28]. This proportion suggests an increase in heat absorption directly related to the concentration of dark surfaces within the city. In the London Borough of Camden for instance, paved and built areas make up 43% of the land cover[29].

---

[26] Wkipidia
[27] English Nature Report 498, 2003, Green roofs: their existing status and potential for conserving biodiversity in urban areas, English Nature Research Reports.
[28] ODPM, Generalised land use data
[29] *Ibid.*

Surface	Material	Albedo
Roofs	Smooth Asphalt	0.07
	Asphalt	0.10 - 0.15
	Tar and Gravel	0.8 - 0.18
	Tile	0.10 - 0.35
	Slate	0.10
	Corrugated Iron	0.10 - 0.16
	Highly Reflective roof after weathering	0.6 - 0.7
Vegetation	Deciduous Plants	0.20 - 0.30
	Dry Grass	0.30
	Deciduous woodlands	0.15 - 0.20
	Coniferous woodlands	0.10 - 0.15

Figure 6 Average Surface Albedo (source: English Nature Report 498)

According to research from LBNL, black surfaces – such as traditional roofing materials – reach 70 degrees F. (40 degrees C.) hotter than the most reflective white surfaces in the sun. If those dark surfaces are roofs, some of the heat collected by the roof is transferred inside, creating a need for more an intensive cooling measure.

3.1.2 Green space reduction

The reduction of green space also influences the temperature within cities. The shading capability of trees and other flora, as well as their ability to retain and release moisture into the environment (evaporative cooling) makes them excellent measures in controlling overheating in the city. The reduction of green space and therefore evaporative cooling in highly developed urban areas results in an increase of temperature.

3.1.3 Urban density

The concentration of built forms in urban areas affects the occurrence of UHI and can have effect on all the previously mentioned issues. For instance, a very dense city such a Tokyo has higher concentrations of tall buildings, people and land development than most other cities, As a result it could be assumed that thermal gains would increase due to anthropogenic activity, that wind may be reduced, or increased as a result of the occurrence of tall building, and that the amount of dark and non – vegetative surfaces would increase – further amplifying solar thermal heat gains.

Similarly, dense urban areas retain more heat than rural areas. The diurnal effect, in regards to temperature is altered due to the high thermal massing in urban areas. The large amounts of concrete and asphalt in cities are excellent at absorbing radiation and storing heat. During the day, the high thermal mass of urban development heats slowly and is released throughout the night. This differs to the occurrences found in rural environments where the thermal mass concentrations tend to be dispersed and there are greater levels of green space.

Within a rural environment, heat surrounding building development occurs in a more direct manner. The absence of high concentrations of thermal mass allows a more or less immediate response to the surrounding temperature. Likewise, when the temperature decreases in the night, the rural landscape reacts immediately. Additionally, the presence of vegetation allows rural environments to stay cooler in the morning due to evaporative cooling[30]

Anthropogenic heat gains are those heat gains which are created by the presence of people, and increase where these populations are most dense. These heat gains are a result of increased vehicular traffic, cooking, increased population density, the use of air conditioners and other equipment among other human activity[31].

3.1.4 Geography and Weather

The geographical attributes of a territory, in terms of physical characteristics such as valleys and mountains, or the geographical location of a city has significant influence on the amplification, or reduction of UHI[32]. Studies conducted in Zaragoza, Spain on topography and vegetation cover on the influence of UHI noted that the relationship between elevation and temperature is negative confirming that depressed areas accumulate hot air areas and favour the persistence of warmer conditions[33]. These would imply that London, which is located in a basin, is more susceptible to the effect of UHI. The city is situated within a low flood plain and surrounded by hills. This landscape suggests warm bodies of air could more easily be contained, or trapped within the region.

[30] Quattrochi, Dale, High spatial resolution airborne multispectral thermal infrared data to support analysis and modeling TASks in EOS IDS Project Atlanta.
[31] Action Energy, 2002, Greenfield: Interface Publishing.
[32] Pon et al, 2000, Existing climate data sources and their use in heat island research, Urban Heat Island Group, Berkeley, Chpt 1, pp14.
[33] Serrano et al., 2004, **Study of** Land cover and Population Density Influences on Urban Heat Island in Tropical Cities by Using Remote Sensing and GIS: A Methodological Consideration, *3rd Fig annual conference,* October.

Geographic location and weather typologies are often synonymous, UHI can either develop favourably, or be reduced by weather patterns typical of a geographic area[34]. Weather in the central London areas has historically been temperate, and favourable to quell the effects of UHI. However, it should be noted that over the past 50 years, and specifically within the last 25 years, temperatures recorded at Heathrow have shown consistent evidence of a warming trend[35]. The decrease of urban heat loss due to urban planning obstruction of airflows and therefore to wind speed. Wind is able to take excess heat away from buildings through convection, and thus, reduced wind speeds take away heat less effectively[36]

3.2 Effects of urban heat island on energy consumption

As the temperature of the earth surface rises, so too does the demand for internal conditioning. Energy consumption carbon emissions also increase, contributing to global warming.

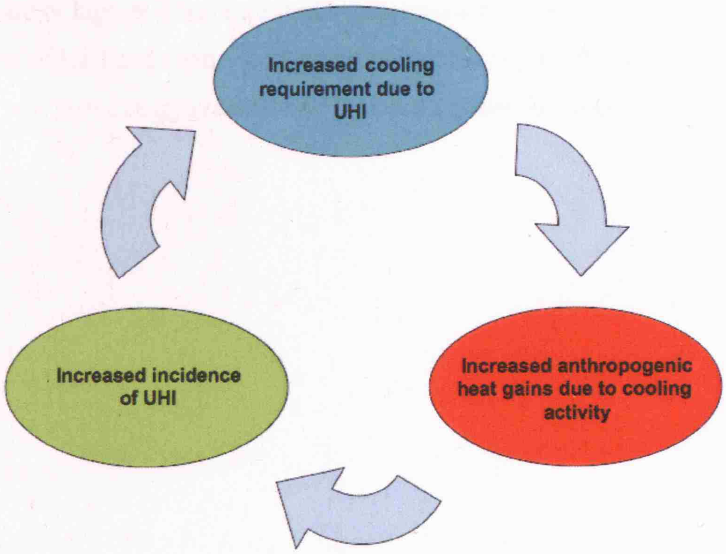


Figure 7: UHI cycle more cooling creates more heat and then requires more cooling

---

[34] Szegedi et al. 2003.

[35] http://www.roehampton.ac.uk/weather/pastcl.asp#modrec, Rohampton University of Surry, Rohampton Weather Website A 300 YEAR PERSPECTIVE ON PAST CLIMATIC CHANGE IN LONDON

[36] Baker et al, Energy and Environment in Architecture: A technical Design Guide, E&FN Spon, London, pp20.

This paradox is also true on the local scale. Figure 7 illustrates this cycle. Increased cooling is required as a result of UHI. The increase of cooling increases anthropogenic heat gains amplifying the incidence of UHI. Finally, more cooling is required to offset the effect of UHI. The increase in energy consumption resulting from the UHI effect is suggested to be between 10 – 60%. In the US it is advised that a full 17% of energy consumption is used for the purposes of cooling at an annual cost of 40 billion dollars[37].

In the UK cooling (including air conditioning, chillers, fans etc...) in office building accounts for 14% of energy consumption[38]. Internationally, however, the UK uses a minimal amount of energy for cooling comparatively speaking. Energy used for cooling in the United States for instance is 20 times greater than that of the UK, and in Japan it is 50 times greater[39]

1994 figures indicate in the UK, air conditioning accounted for the consumption of 13.3 TWh of electricity causing approximately 2 million tonnes of carbon emissions[40].
The use of high performance roofing materials presents a significant opportunity to reduce the effects of UHI and energy consumption by diminishing the need for excess summertime cooling. This potential energy reduction will directly affect the reduction of carbon emission.

[37] EPA, Environmental Protection Agency
[38] Scrace, Ivan, 2000, White-collar CO2 Energy consumption in the service sector, The Association for the Conservation of Energy, London, August.
[39] Hitchin, ER, 2000, UK Carbon emissions from air conditioning in the next two decades, BRE.
[40] *ibid*

4.0 Green and reflective roofs as a means to reduce UHI

UHI mitigation strategies take a variety of forms. The most advocated strategies include the increase of green space as well as the use of reflective materials on surfaces with direct solar exposure. The implementation of these strategies will not only accomplish a reduction of UHI effect, but also reduce energy levels used for cooling. This causes a subsequent reduction of CO_2 emissions, as well. Studies have shown that the presence of green roofs reduced surface temperatures by means of evaporation, water retention and shade.

The use of reflective surfaces, as opposed to typically dark roofing and paving materials, as well as the increase of urban green spaces can reduce the effect of solar radiation, thereby reducing the cooling requirements for a conditioned space. A reflective coating, when applied to the exterior of a building, is designed to reflect incident shortwave solar radiation, thereby reducing the cooling requirements for a conditioned space[41]. In a similar manner, the increase of green space through the use of green roofing systems also has equally positive effect on the occurrence of UHI.

4.1 Roofing Strategies

This chapter systematically presents the positive and negative aspects of green and reflective roofing technologies, relative to their temperature reduction and energy conservation impacts. It does so by addressing some major questions: Firstly, the question of energy reduction – how will a technology affect energy consumption and how can it be reduced. As outlined earlier, the consumption of energy for heating and cooling within the commercial and industrial sector accounts for the majority of the world's CO_2 emissions, and is therefore a priority in the consideration of a sustainable future. Secondly, what impact will the technology have on the environment? Ideally it should improve on the quality of living in terms of health and comfort while not damaging or interfering with the quality of the natural environment. And thirdly, the life cycle of the technology must always be taken into account. What measures must be made for maintenance and renewal of the product in question and how will these factors contribute to its viability in terms of sustainability?

[41] Zarr R, 1998, Analytical Study of Residential Buildings with Reflective Roofs, National Institute of Standards and Technology.

Research has shown that the use of high reflectivity of certain building materials, as well as the use of urban vegetation on and around buildings, can have positive effects on building energy consumption[42]. These savings can occur on the scale of individual buildings, reducing internal temperatures of environments, as well as on the urban scale, by reducing the heat within the urban context.

The amount of energy required to cool a building is affected by many factors, one of which is the roofing. The impact that a roof has on energy usage depends upon the climate, the orientation, thickness and quality of insulation, reflectivity of the roof's surface, and how well the roof has been maintained. The building fabric also accounts for inefficiencies in regards to energy. Air infiltration, poor insulation and resulting fabric heat loss all affect the efficiency of the building[43]. Together these factors influence the amount of cooling energy a building requires.

Roofing Strategy	benefit to energy consumption	positive impact of the environment	Sustainable life cycle costs
Green roof	can reduce energy consumption for cooling	improves air quality, reduces health issues associated with increased temperatures	increases the life span of the roofing membrane thereby extending life of roof
		reduces CO2 emissions associated with energy consumption	can be high maintenance
High performance reflective roof	can reduce energy consumption for cooling	improves air quality by reducing temperature levels, reduces health issues associated with increased temperatures	low initial investment, and low maintenance costs
		reduces CO2 emissions associated with energy consumption	can be high maintenance

Figure 8 Sustainability of green and reflective roofing. The above table summarises the positive aspects of the various roofing strategies.

[42] Taha et al, 1988, Residential Cooling Loads and the Urban Heat Island: The Effects of Albedo, Building and Environment, Vol. 23, No. 4, pp. 271.
[43] Mc Mullan, 2002, Environmental Science in Building, Palgrave, London.

4.2 The Benefits of Green Roofing

Green roofs have been used in construction of dwellings for millennia, yet the benefits of this technology seem to have only recently been rediscovered in the modern context. The benefits of green roofing systems are many, and range from superficial improvements, such as improving aesthetic qualities, to more sustainable issues such as energy savings. The mechanisms in place which help reduce energy consumption (of cooling or otherwise) include an increased U value, evaporative cooling and the provision of shade. Albedo plays a minor role in reducing surface temperatures in that most vegetation has a higher albedo than traditional roofing materials.

4.2.1 UHI mitigation: The beneficial aspects of green roofing

By implementing green roof strategies, the effects of UHI can be reduced therefore also reducing energy consumption for cooling, and carbon emissions derived from energy consumption.

4.2.2 Reduction of temperatures

Evaporative cooling is a system in which latent heat of evaporation is used to carry heat away from an object to cool it. In this case evaporisation includes the sum of water used by vegetation through transpiration, as well as the additional moisture evaporated from the soil. Evaporisation uses a significant amount of incoming solar energy, cooling both the leaf surface as well as the air around it. The energy used for evaporisation is embodied in the water vapour which prevents it from being converted into heat at the surface[44]. According to research conducted in Toronto the use of green roof created a physical barrier, suppressing the overheating of the roofing membrane. The roofing membrane remained cool by means of shading, insulating and evaporative cooling[45]

Using vegetation as an alternate roofing material alters the interaction between the built structure and the surrounding environment. The use of deciduous trees can reduce the direct radiation from the sun up to 95% in the summer time and 50% in the winter months[46], and directly reduces surrounding temperatures. Studies conducted by LBL Lawrence Berkeley Laboratory suggest that shading provided by 3 mature trees, strategically placed, can reduce annual air conditioning

[44] Bass, Brad. "Urban heat island and its assorted problems: Examining the role of the green roof infrastructure", The Green Roof Infrastructure Monitor, Vol 3 No 1, 2001.
[45] Liu, K, 2002, Energy Efficiency and Environmental Benefits of Rooftop Gardens, Construction Canada, March
[46] Akbari et al, 1990, Summer heat islands, urban trees and white surfaces, ASHRAE Transactions, Vol 6, pt 1 pp1381.

loads by anywhere between 25 and 40%[47]. Naturally, the amount of actual savings depends on the amount of actual surface area of the building be shaded.

4.2.3 Reduction of Energy Consumption

Green roofing can also be an effective method for energy reduction. Green roofs can reduce energy costs in several ways. The ability of the green roof to keep the roof surface air temperature cool in the summer reduces cooling loads. In the same manner, when green roofs are used in conjunction with each other, on a larger urban scale, they have the ability to reduce the effects of the urban heat island. Even a slight temperature drop resulting from the increase of urban green space would lower energy costs for the entire region during peak hours. Additionally, the green roof improves the building fabric of the structure providing additional insulation, and providing a barrier to the elements[48]

An ASHRAE simulation conducted by the City of Chicago of their City Hall green roof showed that every one degree Fahrenheit decrease in ambient air temperature results in a 1.2% drop in cooling energy use. The study suggests that if, over a period of ten years or more, all of the buildings in Chicago were retrofitted with green roofs, (30% of the total land area), this would yield savings of $100,000,000 annually from reduced cooling load requirements in all of the buildings in Chicago[49]. Additionally, a study led by Hashem Akbari in Toronto concluded that if heat-island-reducing measures, including cool roofs, were adopted widely, the city could save more than $10 million a year on energy costs[50].

The term U Value refers to the level of thermal transmittance, or the ability for heat energy to move through a barrier (i.e. wall or roof) through conductance[51]. The increase in building materials in order to construct the green roofing system accounts for a reduction of thermal transmittance and thus, better performance of the building fabric. According to research conducted in Toronto the use of a green roof significantly reduced the heat flow through the building fabric, reducing the demand for comfort conditioning within the building[52]

---

[47] Akbari, H, Rosenfelfd, A, Taha, H, 1990, Summer Heat Islands, Urban Trees and White Surfaces, ASHRAE Transactions, Vol.96, pt1, pp. 1381-1388
[48] Bass, B, 2001, Reducing the Urban Heat and its Associate Problems, *Green Roof Infrastructure*, Vol3, no1.
[49] EPA, 2004, Chicago's Heat Island Reduction Activities, http://www.epa.gov/heatisland/pilot/chic_activities.html.
[50] Bass, B, 1999, Modelling the Impact of Green Roof Infrastructure on the Urban Heat Islanf in Toronto, Environment Canada.
[51] Mc Mullan, 2002, Environmental Science in Building, Palgrave, London.
[52] Liu, K, 2002, Energy Efficiency and Environmental Benefits of Roof Top Gardens

4.2.4 Reduction of carbon emissions:

Finally, green roofs might benefit the climate, as well. The increase of plant life required by green roofs acts as filters and help absorb excess greenhouse gases (primarily CO2 in the urban context) as well as provide oxygen. Green roofs have both shown to absorb green house gases as well as filter particulate in the air[53]. The reduction of energy consumption will inevitably lead to a reduction of carbon emissions. This reduction would vary depending on type of energy source.

4.2.5 Additional benefits:

In addition to benefits supporting the reduction of UHI and its associated effects, green roofs can improve health directly by improving air quality. Reducing the temperatures in urban areas reduces the prevalence of smog, directly affecting the prevalence of respiratory ailments. Green roofs also protect the roofing membrane thereby extending the life of the roof[54]. A vegetated roof, on average, can be expected to prolong the service of the life of a conventional roof by at least 20 years[55]. Green roofs have also been widely advocated for their benefit to storm water management[56].

4.2.6 Considerations:

Although there are many benefits to green roofing, some considerations should also be addressed when considering the overall applicability of the technology. Maintenance and repair can be higher for a green roof, for instance, repairing a leak would be both cost and labour intensive. Initial investments in green roofing are high relative to reflective roofing. Installation of a green roof may also require the building to have additional structure in order to support the additional weight. Cost ranges depend on the type of roof, intensive or extensive, as well as the planting matter.

---

[53] Goom, Stephanie, 2003, Green Roofing, The Canadian Centre for Pollution Prevention.
[54] Charlie Miller, 1998, Extensive Green Roofs, Roofscapes inc.
[55] Zwermann, Karl, 200?, ZVG, Zentralverband Gartenbau.
[56] For information on these benefits consult Energy Star, http://www.energystar.gov/index

4.3 Reflective roofing

Light-colored roofing is an efficient method of lowering the surface temperature of buildings. However, since the use of air conditioning became common practice, this method has been largely ignored. On average, 25% of urban landscape in London is developed as building and roads[57]. This means that more than 60% of the rooftops are dark colored. Dark rooftops absorb and radiate heat causing outdoor air temperatures to rise, thus adding to the Urban Heat Island effect. A cool roof is a roof that is highly reflective keeping roof temperatures lower than that of a traditional roof surface material[58].

To understand the manner in which a reflective roof coating functions, the composition of solar radiance must first be examined. Solar radiation is made up of three forms of energy: about 5 percent ultraviolet, 45 percent visible light and 50 percent infrared. When solar energy comes in contact with a surface, it is treated in different manners. For reflective roofing materials, the largest portion is reflected; however, infrared energy is released into the atmosphere. A portion of this heat energy is transferred through convection with the surface air directly on the roof. The remaining heat energy is transferred into the building through convection[59]. Cool roofs reflect heat well across the entire solar spectrum. The less solar radiation materials absorb, the cooler they are. High performance roofing materials radiate any absorbed heat away from the surface[60] In terms of roofing material it is generally understood that reflectivity has a greater effect in reducing the transfer of heat energy from the sun than emissivity.

4.3.1 Reduction of temperatures

The use of light coloured roofing materials as well as the use of reflective roofing materials can effectively reduce both the interior and surrounding temperatures. Typically, in the UK, a roof with direct exposure will see temperatures of about 35°C for a light coloured surface and up to 45°C for a dark coloured surface, given an outside temperature of 30°C and an interior temperature conditioned to 25°C[61]. According to Lawrence Berkeley National Laboratory, at an ambient temperature of 98 degrees Fahrenheit (36.7 degrees Celsius) , raising a roof's reflectivity from 0.25 to 0.40 while keeping emissivity constant, results in a surface temperature reduction of

[57] ODPM, 2004, Generalised land use, England.
[58] Desjarlais, Petrie et al., 2001, ORNL. National Laboratory's Building Envelope Program.
[59] Mc Mullan, 2002, Environmental Science in Building, Palgrave, London.
[60] EPA, Heat Island Effect, Cool Roofs, http://www.epa.gov/heatisland/strategies
[61] Baker, Nick, 2000, Energy and environment in architecture: A technical design guide.

13 degrees Fahrenheit (7.2 degrees Celsius). A change in a roof's emissivity from 0.75 to 0.90 while keeping reflectivity constant results in a surface temperature reduction of only 2 degrees.

4.3.2 Reduction of Energy Consumption

The energy savings associated with reflective and light coloured roof coatings can vary dramatically depending on the level of insulation used and climate in which it is being used. The lower the ceiling insulation the higher the energy savings[62]; additionally there are greater energy savings in sunny and hot climates[63]. However, most studies suggest the use of high performance reflective roofing will see an energy savings between 5% and 30% depending on peak and off peak loads. Research has found, In the case of entire community participation, where the temperature drops 1 C, everyone's cooling load is reduced, even those buildings that are not directly shaded, or that still have dark roofs. Further research indicates 18% direct energy savings when the outside air temperature is reduced by only 2 C[64].

Unlike a green roof which takes a certain amount of time to grow and mature, and see its full sustainable potential, reflective roof coatings provide almost instant gratification[65]. According to studies, highly reflective roof coatings can reduce cooling costs by up to 30%[66]. A Florida monitoring the effect of cooling load for 5 residential buildings suggests an average reduction of 30% on summertime cooling loads[67].

4.3.3 Reduction of carbon emissions

The reduction of energy consumption will inevitably lead to a reduction of carbon emissions. This reduction would vary depending on type of energy source.

---

62 Eilert, Patric,Pacific 2000, High Albedo (Cool) Roofs, Gas and Electric Company, pp. 7.
63 *ibid*
64 Rosenfeld, H, Arthur, 1997, Painting the Town White and Green, MIT Technology Review, March.
65 Akbari et al, 2001, Measured Energy Savings and Demand Reduction from Reflective Roof Membrane on Large Retail Store in Austin, LBNL, California.
66 Bretz et al, 1992, Implementation of White Surfaces: Materials and Utility Programs, LBNL.
67 Parker, DS, 2002, Laboratory Testing Reflectance Properties of Roofing Material, Florida Energy Centre.

4.3.4 Additional benefits

In addition to benefits supporting the reduction of UHI and its associated effects, high performance reflective roofs can extend the roof life of the building, is simple to apply and upgrade, has a low initial investment and low renewal cost, all aspects that make the use of reflective roofing both cost efficient and attractive[68].

4.3.5 Considerations

As mentioned previously, degradation of roof performance needs to be taken into consideration. Due to the nature of the technology, the high albedo surface greatly depends on the level of maintenance invested into the project. A contaminated roof (contaminated by atmospheric particulate, natural refuse etc...) will have a dramatic decrease in reflectivity. Although maintenance of these roofs can greatly vary depending on weather, it is suggested that regardless of scheduled cleanings, even the highest quality reflective roof coating will lose between 10% and 30% of its reflective properties within the first three years of exposure[69]

It should be noted, however, that the use of reflective roofing material has the potential to increase the heating demands in the winter[70], in some cases to significant levels. However, further studies conducted by the Lawrence Berkeley National Laboratory propose the energy benefits of reflective coating during the summer months more than make up for the winter loss.

Using reflective material could potentially cause glare problems for any person or building in direct line of sight with the roof. This glare problem can have outcomes other than visual discomfort such as increasing internal temperatures of buildings adjacent to the reflective roof[71].

---

[68] For information on these benefits consult Energy Star, http://www.energystar.gov/index
[69] Bretz et al, 1992, Implementation of White Surfaces: Materials and Utility Programs, LBNL.
[70] *ibid*
[71] Parker, DS, 2002, Laboratory Testing Reflectance Properties of Roofing Material, Florida Energy Centre.

5.0 Conclusions:

There is a need for additional cooling in the summertime as a result of UHI. Although there may be a reduction of heating requirements in the colder season, studies suggest the added cooling loads far outweigh these savings. Given the physical characteristics of London, including its geography, urban fabric and density, it is sensible to suggestion that the area may be susceptible to the effects of UHI.

The incidence of UHI may be decreased by using implementing green roof, and high performance reflective roof technology. Green roof technology has the potential to reduce surface and therefore ambient temperatures in cities by means of evaporative cooling, shade provision, and an increase U-Value to the urban fabric. Similarly, high performance reflective roofing can also reduce temperatures within the city by increasing the amount of solar energy reflected from roof surfaces. By implementing these technologies within the greater London area, energy consumption for summertime cooling may be reduced significantly, resulting in reduced costs, CO2 emissions and improved health and environment.

Regarding the global context, global warming, and its associated effects may also be curbed by implementing appropriately sustainable roofing technologies.

6.0 Methodology

The method of research used in this project involves the modeling of both green roof and reflective roofing surfaces in a hypothetical urban setting. The models are run and the analysis of each of the aforementioned roof types is carried out.

It should be noted that the mitigation of the UHI effect and the consequent reduction of energy consumption by cooling loads can be achieved by an increase in planting of shade trees, the arrangement and physical properties of the building, as well as by the use of light coloured surfaces other than on roofs. For the purpose of this study, the effectiveness different roof types have on the mitigation of UHI and cooling loads will be tested.

6.1 Modeling

TAS EDSL is used as a modeling tool in order to simulate the effects of roofing materials on the cooling demand and UHI. The results are compared to the results of past research and together provide a guide on the effectiveness of these technologies in the context of the city of London. The purpose of this model is to:

- Investigate the effects of green roof technology on the urban heat island by observing differences in surface temperatures from a base model
- Investigate the effects of reflective roof coatings on the urban heat island by the same means
- Identify patterns in energy use as a result of using either technology
- Recognize the variance (if any) of temperature in relation to a certain percentage of roof covering and or certain levels of implementation of either technology
- Ultimately suggest a strategy, given the above observations, on a viable roofing type for the London climate.

6.1.1 Model design

The model will simulate the effects of green and reflective roofing on a nine block section of a hypothetical urban area. When 'building' a model in TAS EDSL, several steps are used, namely;

- Physically designing the model

- Selecting weather properties
- Zoning the model
- Giving the building elements to simulate construction
- Selecting plant systems and occupation times
- Allowing for internal gains

Each of these steps is followed in order to simulate the running properties of an office building as accurately as possible. The following sections will detail steps mentioned above.

6.1.2 Physical model

The model is designed as one building which represents nine city blocks. The model is essentially one large two storey building, with nine individual and independent (not touching each other) 'rooms' inside. The'rooms' represent the buildings of the city block and are divided by 'halls which represent streets. The 'ceiling' above the halls on the ground floor is constructed entirely of windows which are set to be continuously open, representing open sky above the streets. The first floor is a 1m tall glazed zone which represents the air space directly above the roof surface.

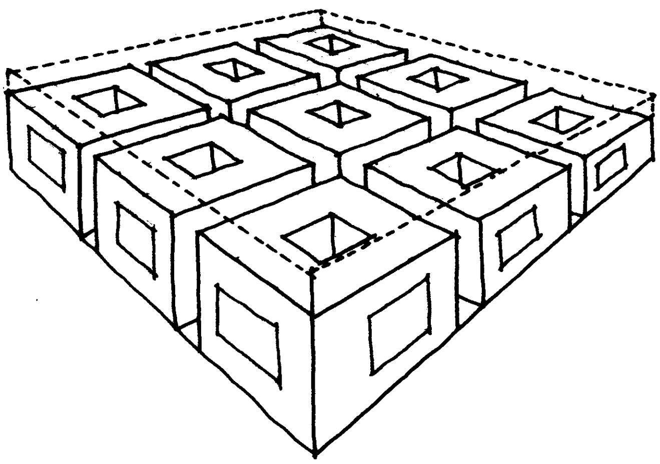


Figure 9 the above sketch illustrates the rationale of the model. Although it is technically a single building, it has been designed in simulate nine separate blocks.

The rationale for designing nine city blocks is to create a more accurate representation of the conditions of UHI. A single block would not accurately take into account the additional heat created by the surrounding structures and would therefore be a poor simulation. Designing nine city blocks in this configuration will allow the model to more accurately simulate the effects of

UHI. Each individual block will simulate surface temperatures that will influence the surrounding ambient temperatures.

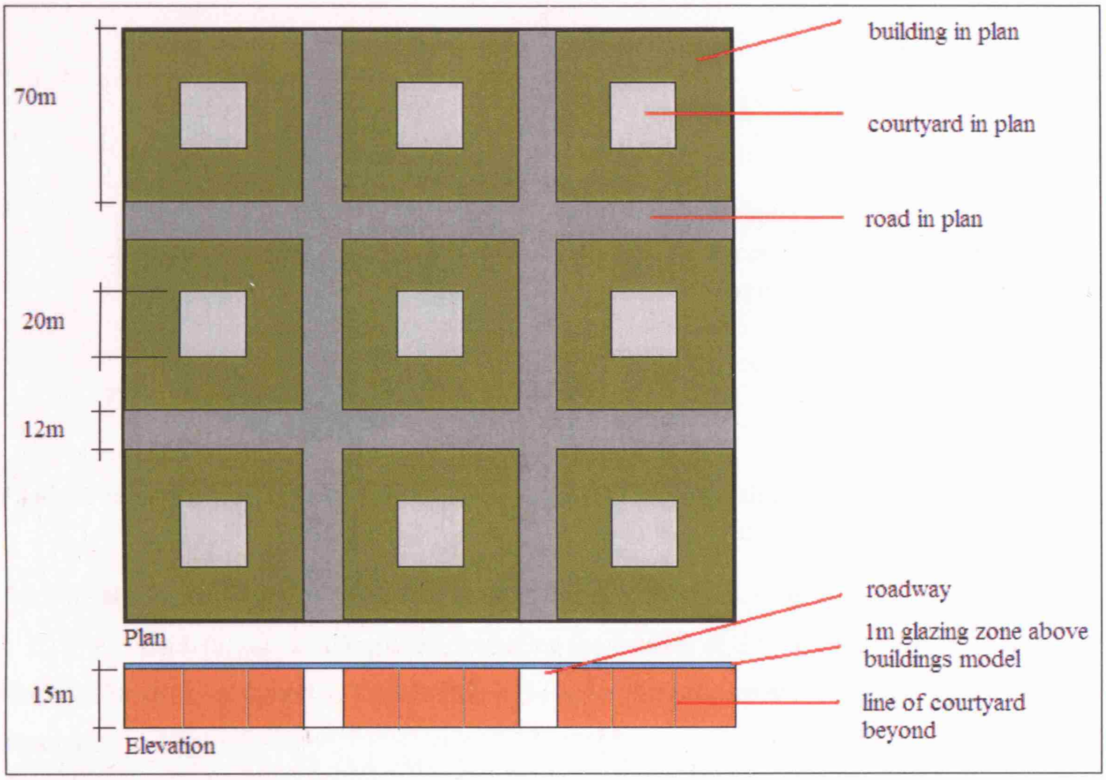


Figure 10: plan and elevation of the nine block model.

The above illustration describes the design of the model. Each of the nine segments represents a building 70m by 70m and 15m in height, with a courtyard of 20m by 20m in the centre. The nine blocks are separated by a grid representing a 12m wide road. A 1m tall zone, covering all nine blocks has also been modeled representing the zone immediately above the buildings.

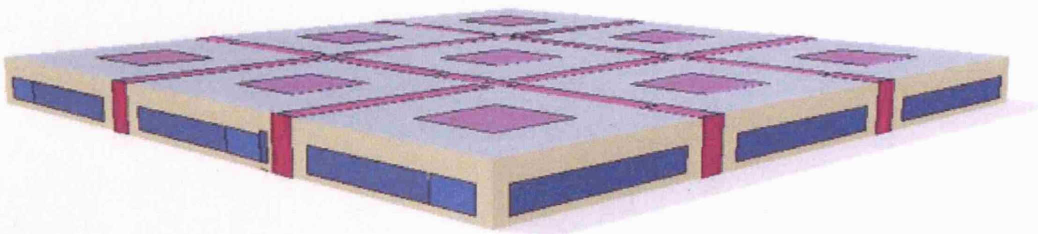


Figure 11: SE perspective of nine block model.

The proportions of the land use in the above described model are as follows:

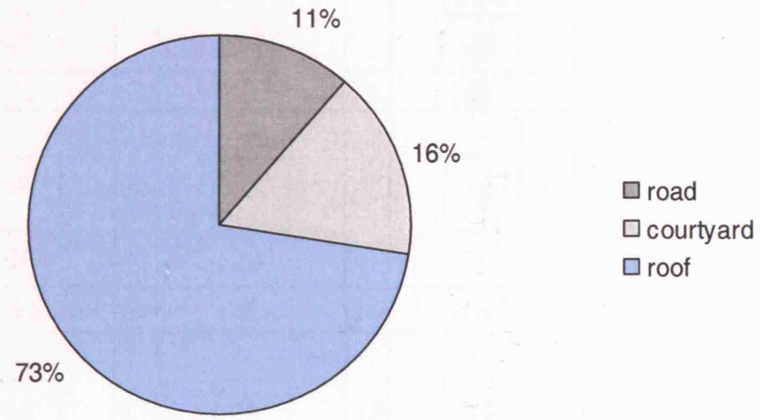


Figure 12 the above chart indicate the proportions of the land use in the simulation (source:KK)

Additional considerations to be made regarding building fabric include:

- Each façade is 40% glazed, including the facades of the interior court yards.

Once the model is designed in TAS Building Designer, the properties must be set for the simulation.

6.1.3 Defining Zones

Defining zones within the TAS model allows for observations and comparisons to be made for specific portions of the model.

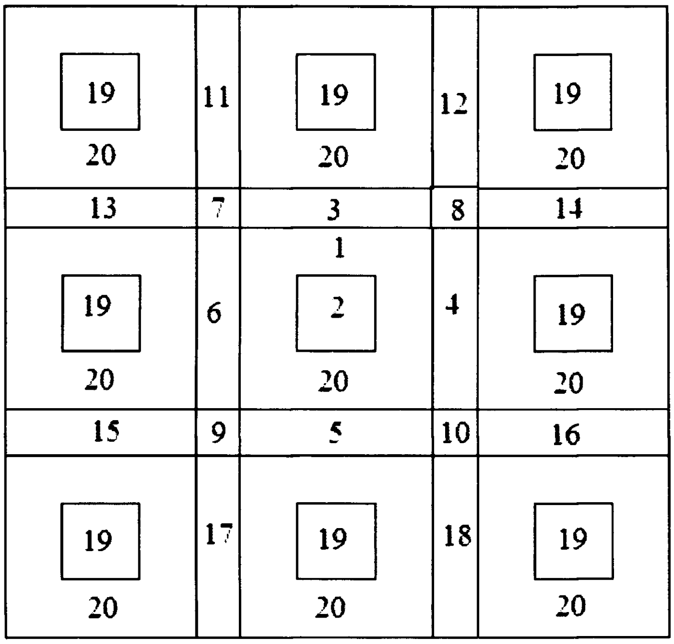


Figure 13 The zones as defined in the base model

The above model includes the following zones:

1. Main Block
2. Main courtyard
3. North main street
4. East main street
5. South main street
6. West main street
7. North west intersection
8. North east intersection
9. South west intersection
10. North east intersection
11. – 18 other roads
19. All other courtyards
20. All other blocks

As mentioned previously, the sections to be monitored include the centre block (block and courtyard), as well as the north, south, east and west sections surrounding it (zones 1 through 6). Thus, the model is zoned accordingly, where the centre block and surrounding street zones immediately opposite the centre block are defined individually. The surrounding blocks are all treated generically and are grouped together with the zones despite geographic location. For instance, the north east block and the south west block are treated as the same zone. This will allow analysis of surface and zone temperatures for the main block. However, as the model is still technically one building, energy loads will be shown for the entire model.

6.1.4 Setting the weather properties

TAS enables the model to simulate a certain day, set of days or year of weather data in order to replicate results similar to that of a real building. In this instance, where cooling loads and surface temperatures are to be monitored, selecting a date with appropriate weather can be beneficial in demonstrating the effectiveness, or lack of effectiveness in the given technology. The base model, and all further models derived from the base will use the same weather file in order for direct comparisons to be made.

In this experiment the weather data file reproduces the climate of London Heathrow, for day 207 for weather data collected from the year 1980. This date is selected based on the characteristics of the weather that specific day. In this case, day 207 offers a high level of solar radiation, relatively consistent wind speeds and direction, as well as relatively warm temperatures.

6.1.5 Building fabric

The building fabric of the base model is composed of three major elements. The roof, the glazing surface and the masonry walls. These are proportioned in order to represent a typical office block. The break down of surface areas is as follows:

Surface	Roof area m2	Masonry area m2	Glazing area m2	Total m2
Roof	4000	0	0	4000
North wall exterior		630	420	1050
East wall exterior		630	420	1050
South wall exterior		630	420	1050
West wall exterior		630	420	1050
North wall courtyard		270	180	450
East wall courtyard		270	180	450
South wall courtyard		270	180	450
West wall courtyard		270	180	450
	4000	3600	2400	10000

Figure 14 The above table indicates the proportions of surface areas within the base model.

The composition of the building fabric greatly influences the energy loads of buildings, and, in this case, will change given the different types of roofing technologies being examined. For the base model, which all models are derived from, there is a standard set of building materials being used and are as follows:

Aperture	Material	Width	Solar Transmittance	External Emissivity	Internal emissivity	conductivity	U-value horizontal	upward	downward
Building window	6 mm kappa float	6.00	0.63	0.85	0.85	2.60	1.80	1.91	1.68
	12 mm airspace	12.00	0.00						
	6 mm clear float	6.00	0.78						
zone divider	10 mm clear float	10.00	0.70	0.85	0.85	1.00	5.56	6.67	4.55

Figure 15 The above table indicates the construction of the windows and the corresponding U Values.

Building Element	Composition	width (mm)	conductivity (W/m C)	Density (kg/m2)	Emissivity external	Emissivity internal	Conductance (W/m C)	External solar absorptance	U value horizontal	upward	downward
Roof	accoustical tile	20.00	0.06	288.00	0.94	0.9	1.297	0.92	1.063	1.098	1.019
	200 mm air space	200.00	0.00	0.00							
	concrete 3%	150.00	0.87	1800.00							
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
	grey slate	10.00	2.00	2700.00							
Typical exterior wall	light weight plaster	25.00	0.08	400.00	0.93	0.9	0.381	0.725	0.358	0.362	0.353
	aerated concrete block	100.00	0.25	800.00							
	glass fibre	55.00	0.04	25.00							
	50mm air space	50.00	0.00	0.00							
	brickwork	105.00	0.70	1700.00							
Asphalt road	asphalt	100.00	0.43	1600.00	0.9	0.95	0.278	0.9	0.265	0.267	0.262
	concreet screed	50.00	1.28	2100.00							
	concrete 3%	125.00	0.87	1800.00							
	crushed brick aggregate	75.00	0.55	1580.00							
	sand dry	1000.00	0.33	1515.00							
	plastic	5.00	0.50	1050.00							
	surface finish .9 absorptivity	0.10	999.99	0.00							
Courtyard floor	terrazzo	25.00	1.75	2400.00	0.91	0.9	0.296	0.76	0.282	0.285	0.279
	concrete screed	50.00	1.28	2100.00							
	concrete 3%	125.00	0.87	1800.00							
	crushed brick aggregate	75.00	0.55	1580.00							
	sand dry	1000.00	0.33	1515.00							
Building floor	terrazzo	25.00	1.75	2400.00	0.91	0.9	0.296	0.76	0.282	0.285	0.279
	concrete screed	50.00	1.28	2100.00							
	concrete 3%	125.00	0.87	1800.00							
	crushed brick aggregate	75.00	0.55	1580.00							
	sand dry	1000.00	0.33	1515.00							

Figure 16 Building elements and material properties and corresponding U-values

Building fabric: Green Roof Model

As discussed previously, the construction of a green roof necessitates the inclusion of several more layers of building material. The model in question represents the typical construction of an extensive green roof. The alterations to the base include the following additions:

Building Element	Composition	width (mm)	conductivity (W/mC)	Density (kg/m2)	Emissivity external	Emissivity internal	Conductance (W/mC)	External solar absorpt	U value		
									horizontal	upward	downward
	acoousticaI tile	20.00	0.06	288.00							
	200 mm air space	200.00	0.00	0.00							
Base roof	concrete 3%	150.00	0.87	1800.00	0.94	0.9	1.297	0.92	1.063	1.098	1.019
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
	grey slate	10.00	2.00	2700.00							
	acoousticaI tile	20.00	0.06	288.00							
	200 mm air space	200.00	0.00	0.00							
	concrete 3%	150.00	0.87	1800.00							
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
Green roof	wool felt underlay	5.00	0.04	160.00	0.9	0.9	0.36	0.4	0.339	0.343	0.335
	earth coasre gravelly	100.00	0.52	2050.00							
	wool felt underlay	10.00	0.04	160.00							
	earth coasre gravelly	100.00	0.52	2050.00							
	polystyrene expanded	50.00	0.04	16.00							

Figure 17 Modeled construction of the base roof compared with the roof with 70% reflectivity

Shaded area indicates building materials used in addition to the base roof

* EDSL TAS has no available materials to accurately represent vegetation. In the case of this study, a material with similar properties to grass (here an organic fiber insulation) is used. The properties of the insulation have also been altered in an attempt to best characterize the effect of vegetation in respect to reflectivity, conductivity and density.

<u>Reflective roof models</u>

Two separate types of reflective roofs are modeled separately, one with 90% reflectivity and a second with 70% reflectivity. These levels of reflectivity correspond to albedo values of a new highly reflective roof coating versus a weathered and slightly deteriorated reflective roof coating. The roof construction changes only slightly with the addition of a reflective surface representing reflectivity mentioned above.

<u>Building fabric: Reflective roof model 70% reflectivity</u>

Building Element	Composition	width (mm)	conductivity (W/mC)	Density (kg/m2)	Emissivity external	Emissivity internal	Conductance (W/mC)	External solar absorpt	U value horizontal	upward	downward
Base roof	acooustical tile	20.00	0.06	288.00	0.94	0.9	1.297	0.92	1.063	1.098	1.019
	200 mm air space	200.00	0.00	0.00							
	concrete 3%	150.00	0.87	1800.00							
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
	grey slate	10.00	2.00	2700.00							
70% reflective roof	acooustical tile	20.00	0.06	288.00	0.9	0.9	1.297	0.3	1.063	1.098	1.019
	200 mm air space	200.00	0.00	0.00							
	concrete 3%	150.00	0.87	1800.00							
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
	grey slate	10.00	2.00	2700.00							
	surface finish	5.00	999.99	0.00							

Figure 18 Modeled construction of the base roof compared with the roof with 70% reflectivity. The shaded area indicates building materials used in addition to the base roof model.

Building Fabric: Reflective roof model 90% reflectivity

Building Element	Composition	width (mm)	conductivity (W/m C)	Density (kg/m2)	Emissivity external	Emissivity internal	Conductance (W/m C)	External solar absorpt	U value horizontal	upward	downward
Base roof	acoousti cal tile	20.00	0.06	288.00	0.94	0.9	1.297	0.92	1.063	1.098	1.019
	200 mm air space	200.00	0.00	0.00							
	concrete 3%	150.00	0.87	1800.00							
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
	grey slate	10.00	2.00	2700.00							
70 % reflective roof	acoousti cal tile	20.00	0.06	288.00	0.9	0.9	1.297	0.3	1.063	1.098	1.019
	200 mm air space	200.00	0.00	0.00							
	concrete 3%	150.00	0.87	1800.00							
	concrete screed	50.00	1.28	2100.00							
	rubber	5.00	0.31	1600.00							
	grey slate	10.00	2.00	2700.00							
	surface finish	5.00	999.99	0.00							

Figure 19 Modeled construction of the base roof compared with the roof with 70% reflectivity. The shaded area indicates building materials used in addition to the base roof model.

6.1.6 Internal Conditions

Plant system

As indicated above, the internal temperature is not to exceed 24 C and lower is not to go below 20 C – indicating the temperatures at which the cooling and heating systems are to initiate[72]. These systems run during the heating and cooling seasons.

Occupation times

The occupational schedule is to reflect typical operating times within an office, where business hours (or times of inhabitance) are between 8:00 and 18:00 on weekdays. From the hours 00:00

[72] Comfort conditions as stated by CIBSE guide A

to 8:00 and 18:00 to 24:00, and on the weekends, the building is considered uninhabited, or where the internal heat gains are inconsequential and have little influence on the internal conditions or the plant system.

Internal heat gains

Set internal heat gains are based on guidelines provided by Energy and Environment in Architecture and reflect the typical internal gains of an office building.

6.2 Evaporative Cooling

An obvious feature of green roofing is the roof's ability to absorb and evaporate water. Essentially, the green roof as a living organism is able to transpire and consume water at a given rate relative to temperature. The evaporation and transpiration of water through the green roof requires a certain amount of heat energy taken from the surrounding environment. This process of extracting heat energy from the surrounding environment effectively reduces temperature. Within the Green Roof model, the amount of heat required to evaporate water is assumed to eliminate the equal amount of energy required for the building cooling load.

This evaporation cannot be modeled in TAS without introducing a cooling plant representing the cooling properties of a green roof. For the purpose of this experiment, the Priestly - Taylor (1972) potential evapotranspiration equation is used to simulate the additional cooling provided by the green roof. This equation estimates the potential evaporation of a given area in mm/m^2 is established.

The Priestley – Taylor method is a generalised equation that predicts the potential evaporation of saturated surfaces. The potential evapotranspiration model used is a two step process, where the potential evapotranspiration from a reference crop, (short clipped grass, 0.12m high, completely covering the ground and with plentiful water supply) is multiplied by a crop coefficient to obtain the potential crop evapotranspiration[73]. Priestley and Taylor

[73] http://www.bsyse.wsu.edu/cropsyst

experimentally derived an average value of 1.26 for this constant in short grasses and humid conditions.

The evaporation calculation used in this model assumes there is unlimited water supply to the green roof, for instance, the roof is subject to heavy or constant rain (i.e. typical British weather) or is irrigated. The Priestley - Taylor method for evapotraspiration is used in this study to evaluate the effectiveness of evaporative cooling effects of the green roof model.
The calculation is as follows:

$$RefET_{pot} = \frac{PT_c \bullet Slope_{vpf} \bullet (Rad_{net} - SoilHeatFlux)}{(Slope_{vpf} + \; y)}$$

where

$RefET_{pot}$ = reference evapotranspiration potential

PT_c	(kPa)	Priestley-Taylor constant location parameter .
Rad_{net}	((MJ/m²)/day)	is the net radiation .provided by TAS
$Slope_{vpf}$	(kPa/°C)	is the slope of saturation vapor pressure function of temperature
γ	(kPa/C)	is the psychrometric constant
SoilHeatFlux	((MJ/m²)/day)	is the soil heat flux.

PT_c	(kPa)	1.26 .
Rad_{net}	((MJ/m²)/day)	25.84
$Slope_{vpf}$	(kPa/°C)	0.0787
γ	(kPa/C)	0.91
SoilHeatFlux	((MJ/m²)/day)	2.584

Figure 20 full calculations appendix A

= .373mm/h

The potential amount of evaporation per hour given the green roof is 0.373 mm/h.

Energy is required for evaporation to take place. To calculate the amount of energy this requires the following calculation is used:

$Q = m \times \lambda$

Where

m = the mass of water evaporated

= 0.37 mm/d x area x density of water

= 0.37 mm/d x 10^{-3} x $4000m^2$ x 1000 kg/m^3

= 1480 kg/h

λ = latent heat of vapourization

= 1480 kJ/kg

Q = 2320 kg/h x 1480 kJ/kg

= 3433600 kJ/d

= 5243200 (kJ/d) / 3600 kJ/kWh

= 953.78 kWh/d / 24h/d

= **39.74 kWh per hour**

Based on a 10 hour running cooling system, if we assume energy from the building is the primary source for evaporation to take place, it is assumed that the amount of water evaporated displaces 397.4 kWh of energy that would have been otherwise used by the plant system of the building. This is a savings per day assuming a 100% green roof coverage of the main block. The output in TAS however, provides data on energy use for the entire nine block model, therefore, it can be assumed that the resulting cooling reduction is relative to 11% green roof coverage, or roughly $1/9^{th}$ of the roof surface.

6.3 Modeling summary

In summary all models are derived from the base model. Additions have been made to the roof constructions in order to simulate the effects of green and reflective roofing. Additional materials added to the green and reflective roofing have changed the properties of the building elements. The external solar absorptance, conductance and U-values of the roofing types have changed based on these material changes and are as follows. The model is based on the aforementioned criteria and the results will reflect these choices.

In order to simulate evaporative properties of plant life, the Priestly – Taylor method of estimating potential evaporation of a surface area is being used. This calculation is selected for its simplicity. Other methods to predict potential evaporation may have also been used, and would produce different results. The effect of evaporative cooling in the green roof modeled here is based on the aforementioned assumptions. Variations noted in the results will be illustrated in the next section.

7.0 Results

The following results are examined in the following categories: variations in surface temperatures, variations in zone temperatures and reduction on cooling load by cooling season.

The surface temperature observations look at variations of the north, east, south and west surfaces between the new roofing technology and the base model. By examining the variations in surface temperatures, it is possible to observe the effects of the new roofing material, in terms of U-value and reflectivity, on the surface conditions of the block.

The zone temperature observations refer to the zone temperatures of the areas surrounding the Main Building; courtyard, and North West, North East, South East and South West intersections. By examining the zone temperatures, it is possible to observe the effect of the roofing material on the temperatures of the surrounding zones These figures imply the ability of the roofing technology being used to potentially reduce temperature in the local area and therefore an overall to the microclimate (UHI).

Cooling load will be looked at to observe the variations based on roofing material. Additionally, calculations will be made in order to discern the effect of the roofing material in relation to reduction, or lack there of, in carbon emissions.

7.1 Green roof model

The following section summarises the results of the green roof model.

7.1.1 Variations in Surface temperatures

	Surface orientation	Daily avg. temp (d.C)	Base temp. (d.C)	Green temp. (d.C)	Change in temp. (d.C)	Change in temp. %
Internal temp	West	24.86	25.55	24.32	-1.22	4.78
	North	24.86	25.62	24.30	-1.33	5.18
	East	24.86	25.76	24.46	-1.30	5.05
	South	24.86	25.65	24.32	-1.33	5.19
	Roof	24.86	27.16	24.04	-3.12	11.48
External temp.	West	24.86	30.63	30.26	-0.37	1.20
	North	24.86	29.91	29.23	-0.68	2.28
	East	24.86	31.77	31.37	-0.40	1.26
	South	24.86	32.00	31.26	-0.74	2.30
	Roof	24.86	35.79	30.98	-4.81	13.45

Figure 21 surface temperatures around main block (^oC)

The results for the green model reflect temperature variations based on the increased U Value and reflectivity of the roof surface of the green roofing system and do not yet take into account provisions for evaporative cooling. As evident, the natures of the green roof building material, which generally have a high thermal capacity, produce quite positive results. The data indicates a decreased roof surface temperature of 4.81 °C or 13.85 %. The surface temperatures of the external walls also indicate a consistent decrease in temperature, with an average of about 1.5%.

Internal surface also show positive results, displaying consistently lowered temperatures in the range of 1.29% to 5.42 % .

7.1.2 Variations in zone temperatures

	Zone orientation	Daily avg. temp. (dC)	Base temp. (d.C)	Green temp. (d.C)	Change in temp. (d.C)	Change in temp. %
Avg. radient temp. (d.C)	courtyard	24.86	35.29	34.99	-0.30	-0.84
	North	24.86	33.56	32.79	-0.77	-2.29
	East	24.86	33.56	33.23	-0.33	-0.98
	South	24.86	33.07	32.58	-0.50	-1.50
	West	24.86	33.73	33.43	-0.31	-0.90
Avg. resultant temp. (d.C)	courtyard	24.86	29.76	29.45	-0.31	-1.04
	North	24.86	28.78	28.24	-0.54	-1.87
	East	24.86	28.78	28.47	-0.31	-1.08
	South	24.86	28.53	28.14	-0.39	-1.38
	West	24.86	28.87	28.58	-0.30	-1.03

Figure 22 temperatures of surrounding zones (°C)

The mean radiant temperature of the green model as compared to the base model reveals quite minimal decreases. The north zone shows the most significant reduction of 2.27 % while the other areas show decreases of inconsequentiality, ranging from a of 0.84% to 1.50 %. Resultant temperature displays quite the same activity, with decreases in temperature from 1.04% to 1.87%. areas.

7.1.3 Overall reduction in energy consumption

	Base	Green	Change in kWh	Change in kWh %
Cooling kWh	367159	351187	-15972	-4.35

Figure 23 overall reduction of energy consumption based on increased U-value and improved reflectivity for cooling season

The cooling load for the cooling season shows a decrease of 4.35% accounting only for changes in U-value and reflectivity from the base model.

7.1.4 Cooling load with evaporative cooling correction

As specified previously, the TAS simulation of the green roof is only capable of simulating the effects of the change in building fabric and the resultant reduction of U Value. The Priestley-Taylor method, described earlier accounts for a 397 kWh reduction in cooling load looking at day 207 given 100% green roof coverage of the main block. As mentioned previously, this reduction is based on an 11% green roof for the entire nine block model. Assuming 100% green roof coverage of the entire nine block model, the energy savings for cooling would be reduced by approximately 10%.

7.2 Reflective roof model: 70% reflectivity

The following section summarises the results of the 70 percent reflectivity roof model.

7.2.1 Variations in surface temperatures

	Surface orientation	Daily avg. temp (d.C)	Base temp. (d.C)	70% temp. (d.C)	Change in temp. (d.C)	Change in temp. %
	West	24.86	25.55	24.90	-0.65	2.55
	North	24.86	25.62	24.94	-0.68	2.66
	East	24.86	25.76	25.08	-0.68	2.63
Internal	South	24.86	25.65	24.96	-0.68	2.67
temp.	Roof	24.86	27.16	25.48	-1.68	6.18
	West	24.86	30.63	30.58	-0.05	0.17
	North	24.86	29.91	29.91	-0.01	0.02
	East	24.86	31.77	31.73	-0.04	0.13
External	South	24.86	32.00	31.99	-0.01	0.02
temp.	Roof	24.86	35.79	28.86	-6.93	19.36

Figure 24 surface temperatures around main block (°C)

The above table indicates that the most drastic improvement in surface temperatures from the base model is to the external roof surface with a temperature reduction of 6.93 °C, or a decrease of 19.36 %. The external wall surfaces indicate temperature variations in a range of .02 % to 0.17%, a negligible variation. The comparison between the internal and external surface temperatures is quite drastic and all values remain quite similar to the daily external temperature.

This occurrence is most likely due to the plant settings (mention in 'Internal Conditions" section), which is set to 24 °C.

7.2.2 Variations in zone temperatures

	Zone orientation	Daily avg. temp. (dC)	Base temp. (d.C)	70% temp. (d.C)	Change in temp. (d.C)	Change in temp. %
Avg. radient temp. (d.C)	courtyard	24.86	35.29	35.50	0.21	0.60
	North	24.86	33.56	33.37	-0.19	-0.56
	East	24.86	33.56	33.64	0.08	0.23
	South	24.86	33.07	33.18	0.11	0.33
	West	24.86	33.73	33.82	0.09	0.27
Avg. resultant temp. (d.C)	courtyard	24.86	29.76	29.84	0.08	0.28
	North	24.86	28.78	28.66	-0.12	-0.41
	East	24.86	28.78	28.80	0.02	0.06
	South	24.86	28.53	28.57	0.04	0.13
	West	24.86	28.87	28.90	0.02	0.08

Figure 25 temperatures of surrounding zones (°C)

The results indicate a very slight increase in temperature of all zones except for the north zone. While these variations are quite minimal, they still imply heat gains from another source. As there has been no change to the U-value and only increase in reflectivity, one may deduce the increased based on the new reflective roofing. A possible cause for this increase may be due to increased glare from the reflective room onto surrounding surfaces, or from the effect of shading on the north side of the building.

7.2.3 Overall reduction in energy consumption during the cooling season

	Base	70.00	Change in kWh	Change in kWh %
Cooling kWh	367159	353214	-13945	-3.80

Figure 26 reduction of overall energy consumption based on increased reflectivity of roofing material for the cooling season

For the cooling season, the 70% reflective roof shows a decrease in overall energy consumption of 3.8 %.

7.3 Reflective roof model 90% reflectivity

The following section summarises the results of the 90 percent reflectivity roof model.

7.3.1 Variations in surface temperature

	Surface orientation	Daily avg. temp (d.C)	Base temp. (d.C)	90% temp. (d.C)	Change in temp. (d.C)	Change in temp. %
Internal temp.	West	24.86	25.55	24.42	-1.12	4.40
	North	24.86	25.62	24.41	-1.21	4.72
	East	24.86	25.76	24.57	-1.19	4.63
	South	24.86	25.65	24.43	-1.22	4.75
	Roof	24.86	27.16	24.30	-2.85	10.50
External temp.	West	24.86	30.63	30.34	-0.29	0.94
	North	24.86	29.91	29.49	-0.43	1.42
	East	24.86	31.77	31.53	-0.24	0.75
	South	24.86	32.00	31.50	-0.50	1.56
	Roof	24.86	35.79	23.71	-12.08	33.75

Figure 27 surface temperatures around main block (°C)

Using a roofing surface with 10% solar absorptivity, properties shows some significant reductions in surface temperatures. Similar to the 70% model, the most apparent reduction in temperature decrease occurred on the roof, at a decrease of 12.08 °C, or 33.75 % in roof temperature. This reduction coincides with previous research on the effects of reflective roof technologies in reducing surface temperatures. This variation is most likely due to not only the increase of reflectivity but a poor U-value as well. As the internal temperatures are set to a value of no greater than 24 °C during office hours, the poor roof insulation would allow the internal condition to significantly effect the external roof temperature.

7.3.2 Variations in zone temperatures

	Zone orientation	Daily avg. temp. (dC)	Base temp. (d.C)	90% temp (d.C)	Change in temp. (d.C)	Change in temp. %
Avg. radient temp. (d.C)	courtyard	24.86	35.29	35.03	-0.26	-0.73
	North	24.86	33.56	32.87	-0.69	2.05
	East	24.86	33.56	33.31	-0.25	0.75
	South	24.86	33.07	32.65	-0.43	1.29
	West	24.86	33.73	33.48	-0.25	0.73
Avg. resultant temp. (d.C)	courtyard	24.86	29.76	29.49	-0.26	0.88
	North	24.86	28.78	28.32	-0.47	1.62
	East	24.86	28.78	28.55	-0.23	0.81
	South	24.86	28.53	28.21	-0.33	1.14
	West	24.86	28.87	28.64	-0.23	0.80

Figure 28 temperatures of surrounding zones (°C)

The reduction in mean radiant temperature for the surrounding zones indicates an overall average decrease of approximately 0.4 °C or 1.11%. The decrease in resultant temperature of the surrounding zones indicates a less obvious decrease at an average of 0.3 °C or 0.1.05%,

7.3.3 Overall reduction in energy consumption during the cooling season

	Base	90.00	Change in kWh	Change in kWh %
Cooling kWh	367159	335751	-31408.31	-8.55

Figure 29 the overall reduction in energy consumption

The reduction in overall energy consumption for the 90 percent reflective roof model is 8.55%.

7.4 Summary of results

7.4.1 Variations in surface temperature

	Surface orientation	Daily avg. temp (d.C)	Base temp. (d.C)	Green temp. (d.C)	70% temp. (d.C)	90% temp. (d.C)
Internal temp.	West	24.86	25.55	-1.22	-0.65	-1.12
	North	24.86	25.62	-1.33	-0.68	-1.21
	East	24.86	25.76	-1.30	-0.68	-1.19
	South	24.86	25.65	-1.33	-0.68	-1.22
	Roof	24.86	27.16	-3.12	-1.68	-2.85
External temp.	West	24.86	30.63	-0.37	-0.05	-0.29
	North	24.86	29.91	-0.68	-0.01	-0.43
	East	24.86	31.77	-0.40	-0.04	-0.24
	South	24.86	32.00	-0.74	-0.01	-0.50
	Roof	24.86	35.79	-4.81	-6.93	-12.08

Figure 30 surface temperatures around main block (°C)

The above table compares the variation in average daily temperatures (°C) of the base main block against the other examined roofing technologies. The internal surfaces of the building show variations in temperature reductions of between 0.65°C and 1.33°C. The external variations also show small reductions in temperature, from 0.01 °C – 0.74 °C. The roof temperatures =, however show significant decreases in surface temperatures. A reduction of 4.81 °C, 6.93 °C and 12.08 °C respectively for each the green, 70 percent and 90 percent reflective roofs. The decrease in surface temperatures is attributed to the increased reflectivity of the surface of each of these materials.

7.4.2 Variations in zone temperatures

	Zone orientation	Daily avg. temp. (dC)	Base temp. (d.C)	Green temp. (d.C)	70% temp. (d.C)	90% temp (d.C)
Avg. radient temp. (d.C)	courtyard	24.86	35.29	-0.30	0.21	-0.26
	North	24.86	33.56	-0.77	-0.19	-0.69
	East	24.86	33.56	-0.33	0.08	-0.25
	South	24.86	33.07	-0.50	0.11	-0.43
	West	24.86	33.73	-0.31	0.09	-0.25
Avg. resultant temp. (d.C)	courtyard	24.86	29.76	-0.31	0.08	-0.26
	North	24.86	28.78	-0.54	-0.12	-0.47
	East	24.86	28.78	-0.31	0.02	-0.23
	South	24.86	28.53	-0.39	0.04	-0.33
	West	24.86	28.87	-0.30	0.02	-0.23

Figure 31 temperatures of surrounding zones (°C)

The green roof model shows the greatest reduction of internal surface temperature. This is due to the high amount of thermal mass in this construction. The high thermal mass has the ability to stabilise the temperatures in the building. During the day, the high thermal massing stores heat and release it during the night, this heavy massing performs similarly during the night by retaining cooler temperatures from night and taking a longer period to warm up during the day. By increasing the thermal mass of the roof surface the surrounding zones of the main block have decreased in temperature. As there is no additional material with significant thermal properties added to both reflective roof types, the reduction of temperature in the surrounding zones of the building can be accredited to the higher reflective surfaces.

7.4.3 Overall reduction in energy consumption during the cooling season

	Green	70	90
% overall energy consumption reduced from base model	4.35	3.80	8.55

Figure 32 reduction of overall energy consumption based on increased U-value and improved reflectivity for cooling season

The 90 percent reflective roof provides the greatest energy saving by reducing overall energy costs during the cooling season by 8.55%.

7.5 Overview

Overall the 90 percent reflective roof shows the greatest benefit in terms of reduction of surface temperatures and reduction of building energy consumption. The green roof and 70 percent reflective roof models also exhibit desirable results. The reduction in energy consumption would, when air conditioning is assumed to be used, result in a reduction of carbon emissions as well. To fully assess the potential of these roofing strategies, cost must also be taken into account.

7.6 Economic Feasibility

In order to determine the financial implications of implementing these technologies, the green roof and reflective roofing systems, an economic study must be considered. This study will take into consideration the capital costs and the running costs compared to a traditional roofing system.

The green roof considering 100% coverage and the reflective roof considering 90% reflectivity will be used to model the economic feasibility.

7.6.1 Capital

In both the case of the green roof and the reflective roof, the capital costs only consider material and the labour of the applied technology. In the case of the green roof it is assumed that the green roof is extensive in type, and the building will not need additional structural reinforcement to support the roof. In this economic study, it is not necessary to take into account the boiler systems as they will be identical.

Green Roof:

The total average costs of labour, roofing membrane, planting medium and vegetation for an extensive roofing system would be approximately 50 GBP/m^2 [(74)]. Given a roof of 4000m^2, the total capital costs for the green roofing system assuming 100% coverage would approximately 200,000 GBP.

Reflective Roofing:

The average price for aluminum reflective paint, including labour assuming 2 coats of paint is given at 16.09 m^2 [(75)] Given a 4000m^2 the total capital costs 64 360 GBP.

7.6.2 Maintenance

The maintenance cost per annum must be calculated in order to devise an accurate cost comparison and to calculate an viable buy back period.

[74] Johnson, J, Newton, J, 2004, A guide to using plants on roofs, walls and pavements, *Building Green*, Mayor of London.

[75] Spon, 2004

Green Roof:

The maintenance costs for many extensive green roof, characterized by the use of low maintenance and indigenous species of plants is considered negligible[76].

Reflective Roof:
The reflective roof does not require additional maintenance above and beyond the maintenance costs of a typical roof therefore the maintenance cost is assumed to be nil.

7.6.3 Energy Demands for Heating and Cooling:

In order to calculate monetary savings, the energy savings must first be calculated. The following results are derived from the TAS model, which does not take into account the evaporative cooling effect of the Green Roof. As mentioned previously, disregarding the additional savings achieved by evaporative cooling, the green roof model shows a 4.35% overall energy reduction for the cooling season, while an 8.55% reduction is achieved in the 90% reflective roofing model.

7.6.4 Running Costs:
To calculate the running cost of the system the energy load must be multiplied by the cost per kWh assuming electricity is being used (electricity is the primary power source for air conditioning). Additionally, an annual maintenance cost must include in the calculation.

By using the following calculation:
Capital + Running Costs x Years,

The total life cycle costs can be calculated. It should be noted that it is suggested that a reflective roof can have a life span of up to 25 years, whereas a green roof can last 50 years or more. For the purpose of this calculation it is assumed that the roof will have a life of 50 years, taking into account 2 capital costs to account for re-painting of the reflective roof.

Green roof	200,000 GBP

[76] Green Roofs, 2003, Research advice notes, British Council for Offices, Corporation of London.

Reflective roof	128,720 GBP

Therefore the lifetime cost of the reflective roof is approximately 35% less than a green roof. A more precise economic evaluation would be required to consider the additional summer and winter cooling loads, and compounded interest, as well as the assumption of re-roofing in entirety.

8.0 Discussion

The results of the modeling have yielded some obvious findings. The use of green and reflective roofing types has exhibited positive results in reducing surface temperatures when compared to the base model roof. Findings indicates that the use of green and reflective roof types have been able to reduce, in some cases significantly, the roof surface temperature of the modeled block as compared to the base model, which represents a typical dark roof construction.

Results

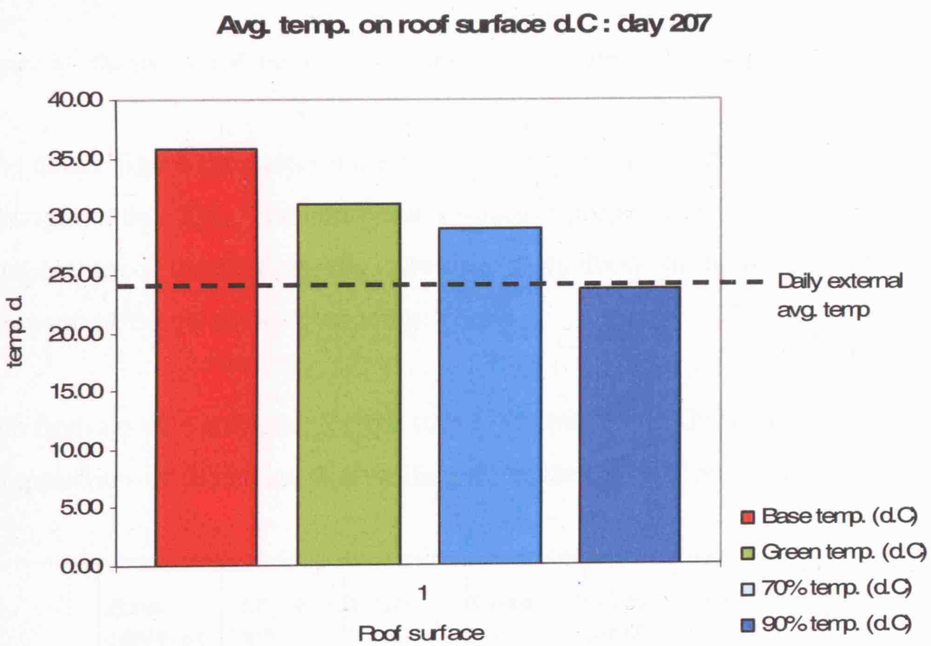


Figure 33 Comparison of average roof temperature (°C) for the different roof types.

The above figure indicates the variations in average daily roof surface temperature (°C) when the external air temperature is 24.86 °C. The green roof displays a 13.5% decrease, the 70 percent reflective roof displays a 19.5% decrease and the 90 percent reflective roof offers a 33.0% decrease in surface temperature compared to the base model. The substantial decrease from the reflective roofs can be both attributed to the reflective properties of the roof and the high U-Values of both. The temperatures of internally conditioned spaces have greater influence on the surface temperatures of the reflective roof as a result of the higher U-Values (as compared with the green roof. If the roof had additional insulation, the effects on cooling by the reflective materials would be reduced.

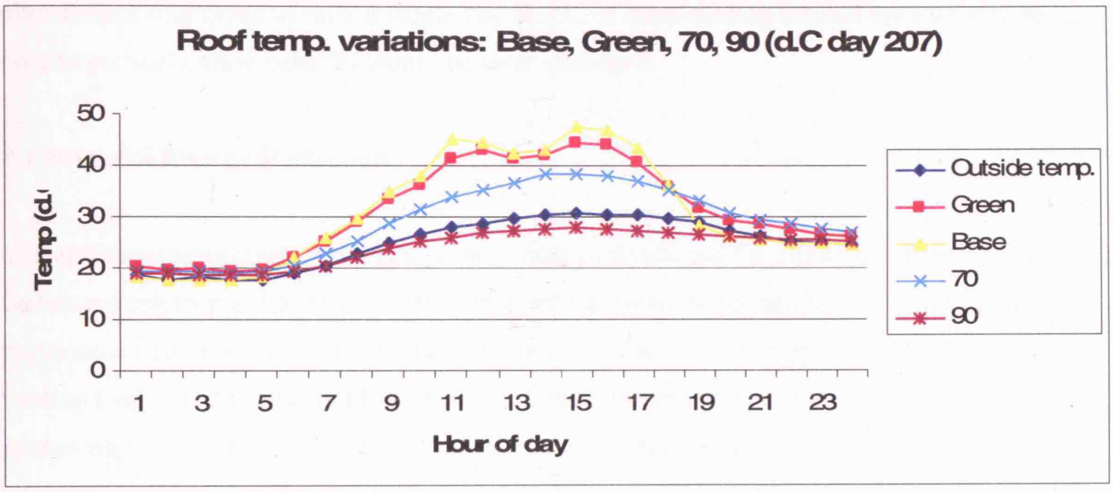


Figure 34 Comparison of roof surface temperature variations (°C) for day 207.

The above figure illustrates the effects of the roofing materials on surface temperatures throughout day 207. The additional insulative properties of the green roof stabalise the temperature of the roof slightly, while the high albedo of the reflective roofs has a dramatic effect on the surface temperature.

The findings also indicate that the roof types modeled exhibit potential to reduce the temperatures of the zones surrounding the main centre block, relative to the base model.

	Zone orientation	Daily avg. temp. (dC)	Base temp. (d.C)	Green temp. (d.C)	70% temp. (d.C)	90% temp (d.C)
Avg. radient temp. (d.C)	courtyard	24.86	35.29	-0.30	0.21	-0.26
	North	24.86	33.56	-0.77	-0.19	-0.69
	East	24.86	33.56	-0.33	0.08	-0.25
	South	24.86	33.07	-0.50	0.11	-0.43
	West	24.86	33.73	-0.31	0.09	-0.25
Avg. resultant temp. (d.C)	courtyard	24.86	29.76	-0.31	0.08	-0.26
	North	24.86	28.78	-0.54	-0.12	-0.47
	East	24.86	28.78	-0.31	0.02	-0.23
	South	24.86	28.53	-0.39	0.04	-0.33
	West	24.86	28.87	-0.30	0.02	-0.23

Figure 35 temperatures of surrounding zones (°C)

Although these effects appear to be minimal, it should be noted that this experiment looked at the alteration of roof types of only a single city block. If these roofing technologies were to be used on a larger scale, their benefits would be more profound.

8.1 Potential Energy Reduction

The ambitious objectives of the UK commitment to Kyoto and the reduction of energy use and carbon emissions provide an excellent social environment for the implementation of high performance roofing materials and the prospective reduction of energy use by reduction of cooling loads. The use of highly reflective coatings or the green roof alternative provides a proven means of energy reduction. However, each technology presents different qualities that either support or refute the use of the system within a certain climates and given certain building uses. For instance, in a large warehouse space, where heavy manual labour takes place, a reflective roof may be more beneficial. Thermal comfort would be met in cooler conditions than in an office due to the high amount of physical activity. The heating deficit would be minimalised during the heating season and the cooling benefits would be suitable during the cooling season. Additionally, the use of reflective roofing materials in non conditioned and seasonally used spaces, such as on the roof of a residential conservatory, would not provide any cooling load reduction, but would improve thermal comfort within the space.

8.2 Reflective roofing

Considering these implications in terms of Kyoto, using reflective roofing surfaces show great potential for reduction of emissions when regarding summertime cooling loads.
The cooling effects of the reflective roofing system show remarkably encouraging results. As supported by numerous studies, the use of reflective roofing can reduce the surface temperatures significantly. The results for the aforementioned model exhibit roof temperature reductions in the range of 33.75%. Given the research observed here, a white roof with 90% reflectivity can reduce the over all energy consumption for a cooling season by 8.55%.

The economic evidence suggests that, due to low maintenance, simplicity of application and its ability to extend roof life, the reflective roof is the most feasible option for energy reducing technology.

However, there are several considerations that must be assumed that have not been discussed in this paper. Given the construction properties and nature of the technology, that being the ability to successfully reflect 90% of the solar radiation that strikes the surface, logic suggests that there will be a significant winter heating penalty. Research conducted by the Lawrence Berkley National Laboratory advises that due to the low angle of sun, and shorter days associated with the winter season would reduce this penalty significantly[77]. When examining the TAS model results describing cooling as well as heating loads, a 90% reflective roof would result in a 2% increase of energy consumption considering the heating period as a result of the increase of heat loss due to the low U Value coupled with the its reflective properties.. In most cases, the summer time cooling benefits outweigh the winter deficit as cooling requires a greater amount of energy than heating.

Another consideration not taken into account in this study is the deterioration of the reflective properties of the roof technology. Although, degradation of albedo occurs differently for different materials, studies suggest that after a 3 year period, a 90% reflective roof may diminish to a 70% or less reflective capacity[78].

8.3 Green roof

The green roof alternative displays benefits with a reduction of overall building energy use of 4.35% over the cooling season without taking into account the additional cooling effects of evapotranspiration. The foremost restriction in adopting the green roof technology on a commercial scale is clearly the initial investment.

Although the green roof model exhibits less successful reductions in surface temperatures given the TAS model, the properties of evaporative cooling cannot be emulated using this program. When considering the true implications of a vegetative covering, the effects on cooling would be significantly amplified. This detail would positively effect the localized temperatures given wide spread use of the system, contributing to the alleviation of UHI.

---

[77] Akbari, H, Konopcki, S, 2001, Measured Energy Savings and Demand Reduction from Reflective Roof Membrane on a Large Retail Store in Austin, Heat Island Group, Environmental Technologies Division Lawrence Berkely National Laboratory, June.
[78] Bretz, S, Akbari, Hashem, Rosenfeld, A, Taha, 1992, Implementation of White Surfaces: Materials and Utility Programs, Lawrence Berkely Laboratory Report 32467.

The unquantifiable and theoretical attributes of the green roof need to be expressed within the discussion in order to fairly portray all improved aspects of the environment given the use of the technology.

9.0 Conclusion

9.1 Method analysis

While the results affirm the positive effects of the green and reflective roofing technologies regarding their ability to reduce roof surface temperatures as well as surrounding zone temperatures (i.e. the UHI) the modeling method may need to be refined in order to produce more accurate and consistent results. To build upon this research, it is suggested that this modeling, which includes the use of a computer model of a hypothetical city block as well as an external calculation to achieve the effects of a green roof could be refined by the use of different or multiple types of evapotranspiration equations. Additional suggestions include:

- the use of different roofing materials to simulate different planting types
- modeling different proportions of both green and reflective roofing materials

The model assumes the use of air conditioned cooling, where the reality is, and not every office uses air conditioning. The results therefore reflect energy savings for only these types of buildings. Where passive cooling is used there would be no cooling load reduction savings for either roof type, however improvements to thermal comfort would be improved. Energy use variations would take place during primarily during the heating season.

9.2 Additional benefits of green roofing

The use of a green roofing system exhibits a potential energy reduction similar to that of reflective roofs. However, there are immeasurable qualities that green roofing technologies also possess. Dr Roger Ulrich, a renowned behavioral scientist, describes the various benefits of the availability and presence of natural environment. It is argued that the provision of a natural surrounding can facilitate a distraction from other external turbulence or personal turmoil, thereby reducing stress and improving health. Additionally, Cimprich's studies on the health benefits of the natural environment further support Ulrich's premise regarding the presence of a natural environment[79]. These studies indicate the stress reducing, and consequential healing properties of interaction with nature as well as the importance of the natural view. It argued that the sick benefit from the additional stimulation to the senses provided by interaction to a natural

[79] Cimprich, B, 1993, Development of an intervention to restore attention in women treated for breast cancer, Cancer Nursing, 16, 83-92.

environment. The book Biophilia Hypothesis, gives a simple explanation to this phenomenon, and this is the fundamental idea that humans have an innately emotional connection to other living organisms[80], essentially, having sensory access to nature, and visual, and physical or otherwise, can improve one's health.

Although, in terms of energy use, and emissions reduction, this attribute has no numerical merit, it still has bearing in the context of sustainability, and can be numerically quantified in other divisions of the sustainable argument. Given the above approach, the psychological qualities of a green roof certainly have potential to reduce health care costs by fostering healthier living. This however is anecdotal, and provides grounds for future study.

The green roof alternative holds great appeal in its creation of additional public space and urban beautification. In regards to intensive roof systems, where access is available, the green space provides additional public areas.

9.3 The appropriate application of roofing technologies

As discussed previously, both technologies present a beneficial outcome in terms of cooling load reduction, however, when all factors are taken into account, the depiction of these sustainable practices reveal major issues. Predicting an appropriate technology for use in London may be a secondary question to predicting the suitability and application purposes. For instance, in terms of winter deficit apparent in the utilization of reflective roofing, the technology may still prove to be quite sufficient in applications where cooler interior temperatures during the winter are acceptable. In warehouses and factories, where machinery and equipment provide significant internal heat gains, and where physical activity increases personal metabolic rates, the cooling effect would be less noticed. Where green roofs were exploited in hospital facilities, or within dense urban developments, the high initial investment could be partially recovered through the health benefits and monetary savings associated with it.

9.4 UK Feasibility: Policy

The benefits of high performance roofing materials in terms of definable energy consumption and climate change are quite profound. The use of these materials presents the advantages to the environment. Yet, in the UK, few sectors show interest in the investment. A major catalyst in the

[80] Wilson, S, Edward, O, 1995, The Biophilia Hypothesis, New York Island Press, April.

commercialization of green alternatives would result from rigorous government policy. Although the retrofit of existing building to new high performance, and sustainable practices can present high initial investment, these can be offset by government incentive and funding. That is not to imply a lack of environmental policy in the UK or the EU. As outlined earlier, the EU government has embraced clear sustainability objectives specifically in the reduction of carbon emissions. For instance, the EU is planning to implement taxation on all energy products, obliging all member states to enforce taxes on energy products to encourage energy efficiency[81]. This tactic of imposition will most likely yield the results desired, however involuntarily. A subsidy program would provide positive incentive to invest.

9.5 Roofing in Context

High density urban development, highly absorptive surfaces and absence of green space has had a negative impact on localized microclimate. The increase of surface temperature due to these factors exhibits consequential increase energy consumption and imply the need for increased climate conditioning. The model demonstrates the impact of typical urban composition on the surrounding environment and suggests the major weight of UHI is caused by the urban fabric itself. Where variables, such as roof types, are introduced, the patterns in surface temperature suggest a strong correlation between roof surface properties and energy consumption during the cooling season assuming the use mechanical cooling systems.

The benefits of high performance highly reflective surfaces exhibit positive effects on reducing surface temperatures and energy loads when the use of air conditioning is assumed. Research suggests that during the heating season, reflective roof technology would in fact cause an increase in energy consumption.

Green roofs have inherently positive effects due to the increase of high thermal massing building materials and resultant increase in U Value. These effects alone show a noticeable reduction in summertime cooling load where mechanical cooling is used. Where evaporative cooling is considered, the cooling affect improves.

In both the reflective and green models, surface temperatures, which display the greatest reduction in temperature, consequently show decreases in surrounding surface and zone

[81] dti Energy White Paper , 2003.

temperatures, suggesting the benefit of these technologies regarding the reduction of urban heat island. Similarly, the use of these technologies shows great potential for the reduction of cooling loads and resultant decline in CO_2 emissions, suggesting the affirmative effects to issue of climate change.

In London, given the typical weather, the application of these technologies may have a greater influence of the heating load than on the cooling load. While the increased U-Value associated with the green roof shows an improvement in regards to energy consumption, the reflective roofing technologies show the opposite.

The reduction or increase of surface temperatures and surrounding local temperatures has significant impact on the building energy consumption. By controlling these variables, the potential the reduction of energy use for mechanical cooling systems presents itself. Reducing the amount of energy consumed by buildings will assist in the reduction of global warming.

10.0 Bibliography

Action Energy, 2002, Greenfield: Interface Publishing.

Akbari et al, 1990, Summer heat islands, urban trees and white surfaces, ASHRAE Transactions, Vol 6, pt 1 pp1381.

Akbari et al, 2001, Measured Energy Savings and Demand Reduction from Reflective Roof Membrane on Large Retail Store in Austin, LBNL, California.

Akbari, H, Konopcki, S, 2001, Measured Energy Savings and Demand Reduction from Reflective Roof Membrane on a Large Retail Store in Austin, Heat Island Group, Environmental Technologies Division Lawrence Berkely National Laboratory, June.

Akbari, H, Rosenfelfd, A, Taha, H, 1990, Summer Heat Islands, Urban Trees and White Surfaces, ASHRAE Transactions, Vol.96, pt1, pp. 1381-1388

Akbari, Hashem, 2000, Urban Heat Island Group, http://eetd.lbl.gov/HeatIsland/.
American Information Administration

Baker et al, Energy and Environment in Architecture: A technical Design Guide, E&FN Spon, London, pp20.

Baker, Nick, 2000, Energy and environment in architecture: A technical design guide.
Barry, R.G, 2003, Atmosphere Weather and Climate, Routledge, Francis Taylor Group, November.

Bass, B, 1999, Modelling the Impact of Green Roof Infrastructure on the Urban Heat Islanf in Toronto, Environment Canada.

Bass, B, 2001, Reducing the Urban Heat and its Associate Problems, *Green Roof Infrastructure*, Vol3, no1.

Bass, B, et al, 2001, Reducing the urban heat island and its associated problems, *The Green Roof Infrastructure*, vol3, no1,.

Bass, Brad. "Urban heat island and its assorted problems: Examining the role of the green roof infrastructure", The Green Roof Infrastructure Monitor, Vol 3 No 1, 2001.

Bretz, S, Akbari, Hashem, Rosenfeld, A, Taha, 1992, Implementation of White Surfaces: Materials and Utility Programs, Lawrence Berkely Laboratory Report 32467.

Charlie Miller, 1998, Extensive Green Roofs, Roofscapes inc.

Cimprich, B, 1993, Development of an intervention to restore attention in women treated for breast cancer, Cancer Nursing, 16, 83-92.

Climate change: a glossary by the Intergovernmental Panel on Climate Change, 1995.

CNN, 2003, Europe swelters under heatwave,
http://www.cnn.com/2003/WORLD/europe/08/06/heatwave

Comfort conditions as stated by CIBSE guide A

Defra, 2005, environmental protection,
http://www.defra.gov.uk/environment/climatechange/01.htm#details

Defra, 2005, http://www.defra.gov.uk/environment/climatechange/02.htm

Desjarlais, Petrie et al., 2001, ORNL. National Laboratory's Building Envelope Program.

Eilert, Patric,Pacific 2000, High Albedo (Cool) Roofs, Gas and Electric Company, pp. 7.

Energy White Paper, 2003, UK, February.

English Nature Report 498, 2003, Green roofs: their existing status and potential for conserving biodiversity in urban areas, English Nature Research Reports.

EPA, 2004, Chicago's Heat Island Reduction Activities,
http://www.epa.gov/heatisland/pilot/chic_activities.html.

EPA, Heat Island Effect, Cool Roofs, http://www.epa.gov/heatisland/strategies

Goom, Stephanie, 2003, Green Roofing, The Canadian Centre for Pollution Prevention.

Green Roofs, 2003, Research advice notes, British Council for Offices, Corporation of London.

GREENHOUSE GASES AND GLOBAL WARMING POTENTIAL VALUES EXCERPT FROM THE *INVENTORY OF U.S. GREENHOUSE EMISSIONS AND SINKS: 1990-2000*

Hitchin, ER, 2000, UK Carbon emissions from air conditioning in the next two decades, BRE.
http://www.bsyse.wsu.edu/cropsyst

http://www.roehampton.ac.uk/weather/pastcl.asp#modrec, Rohampton University of Surry, Rohampton Weather Website A 300 YEAR PERSPECTIVE ON PAST CLIMATIC CHANGE IN LONDON

International Energy Annual, 2002

Johnson, J, Newton, J, 2004, A guide to using plants on roofs, walls and pavements, *Building Green*, Mayor of London.

Kyoto Protocol, 1997

Liu, K, 2002, Energy Efficiency and Environmental Benefits of Rooftop Gardens, Construction Canada, March

Liu, K, 2002, Energy Efficiency and Environmental Benefits of Roof Top Gardens

Marland, G., T.A. Boden, and R. J. Andres. 2003. "Global, Regional, and National CO2 Emissions." In *Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center*, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A

Mc Mullan, 2002, Environmental Science in Building, Palgrave, London.

ODPM, 2004, Generalised Land Use Database: England

OECD Environmental Performance Reviews, 2004, Organisation for Economic Co-operation and Development, January

Parker, DS, 2002, Laboratory Testing Reflectance Properties of Roofing Material, Florida Energy Centre.

Pon et al, 2000, Existing climate data sources and their use in heat island research, Urban Heat Island Group, Berkeley, Chpt 1, pp14.

Quattrochi, Dale, High spatial resolution airborne multispectral thermal infrared data to support analysis and modeling TASks in EOS IDS Project Atlanta.

Rosenfeld, H, Arthur, 1997, Painting the Town White and Green, MIT Technology Review, March.

Scrace, Ivan, 2000, White-collar CO2 Energy consumption in the service sector, The Association for the Conservation of Energy, London, August.

Serrano et al., 2004, **Study of** Land cover and Population Density Influences on Urban Heat Island in Tropical Cities by Using Remote Sensing and GIS: A Methodological Consideration, *3rd Fig annual conference,* October.

Spon, 2004

Taha et al, 1988, Residential Cooling Loads and the Urban Heat Island: The Effects of Albedo, Building and Environment, Vol. 23, No. 4, pp. 271.

Turekian, C. Vaughn, 2001, An analysis of some key questions: climate change.

Wilson, S, Edward, O, 1995, The Biophilia Hypothesis, New York Island Press, April.

World Health Organisation

Zarr R, 1998, Analytical Study of Residential Buildings with Reflective Roofs, National Institute of Standards and Technology.

Zwermann, Karl, 200?, ZVG, Zentralverband Gartenbau.

11.0 Appendix

Appendix 1
Priestley Taylor reference evapotranspiration potential

$$RefET_{pot} = \frac{PT_c \bullet Slope_{vpf} \bullet (Rad_{net} - SoilHeatFlux)}{(Slope_{vpf} + \; y)}$$

where

PT_c	(kPa)	Priestley-Taylor constant location parameter .
Rad_{net}	$((MJ/m^2)/day)$	is the net radiation .
$Slope_{vpf}$	(kPa/°C)	is the slope of saturation vapor pressure function of temperature
γ	(kPa/C)	is the psychrometric constant
SoilHeatFlux	$((MJ/m^2)/day)$	is the soil heat flux.

$$RefET_{pot} = \frac{PT_c \bullet Slope_{vpf} \bullet (Rad_{net} - SoilHeatFlux)}{(Slope_{vpf} + \; y)}$$

PT_c = given as 1.26 for short grasses and humid conditions

$$Slope_{vpf} = \frac{VPsat * 4098}{(T_{avg} + 237.3)^2}$$

VPsat (kPa) is the saturated vapor pressure at average air temperature.
Tavg (°C). is the average air temperature.

$$VPsat = 0.611 * e^{(17.27 *T/ (T+237.3))}$$

$$= 1.32$$

$$Slope_{vpf} = \frac{1.32 \; * \; 4098}{}$$

$$68727.8656$$

$$= 0.0787 \text{ (kPa/C)}$$

Rad_{net} - SoilHeatFlux =
(net radiation given in TAS as 7178)

$$= \frac{7187 * 3600}{1000000}$$

$= 25.84$ Mj/m^2.d

SoilHeatFlux = Rad_{net} * 0.1

Rad_{net} - SoilHeatFlux =

= 23.256

$(Slope_{vpf} + y)$ = is the psychometric constant given by:

$$\gamma = \frac{Cp \cdot P}{0.622 \cdot \lambda}$$

Cp ((MJ/kg)/°C) is the specific heat of air (about about 0.001).
P is the atmospheric pressure (taken as 96 kPa).
λ (MJ/kg) is the latent heat of vaporization.

$$= \frac{0.001 * 101.325}{0.622 * 0.91}$$

= 0.179

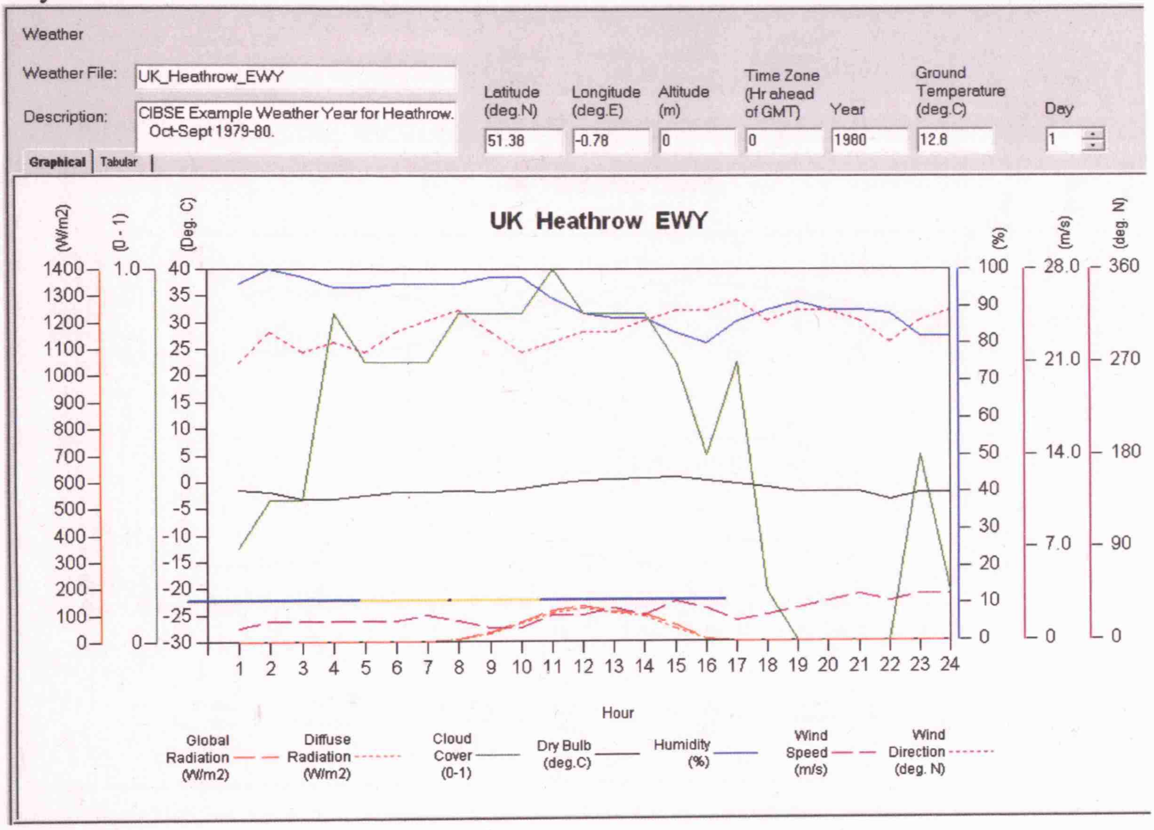
$$RefET_{pot} = \frac{PT_c \bullet Slope_{vpf} \bullet (Rad_{net} - SoilHeatFlux)}{(Slope_{vpf} + y)}$$

$$= \frac{1.26 * 0.0787 * (25.84 - 2.584)}{0.0787 * 0.179}$$

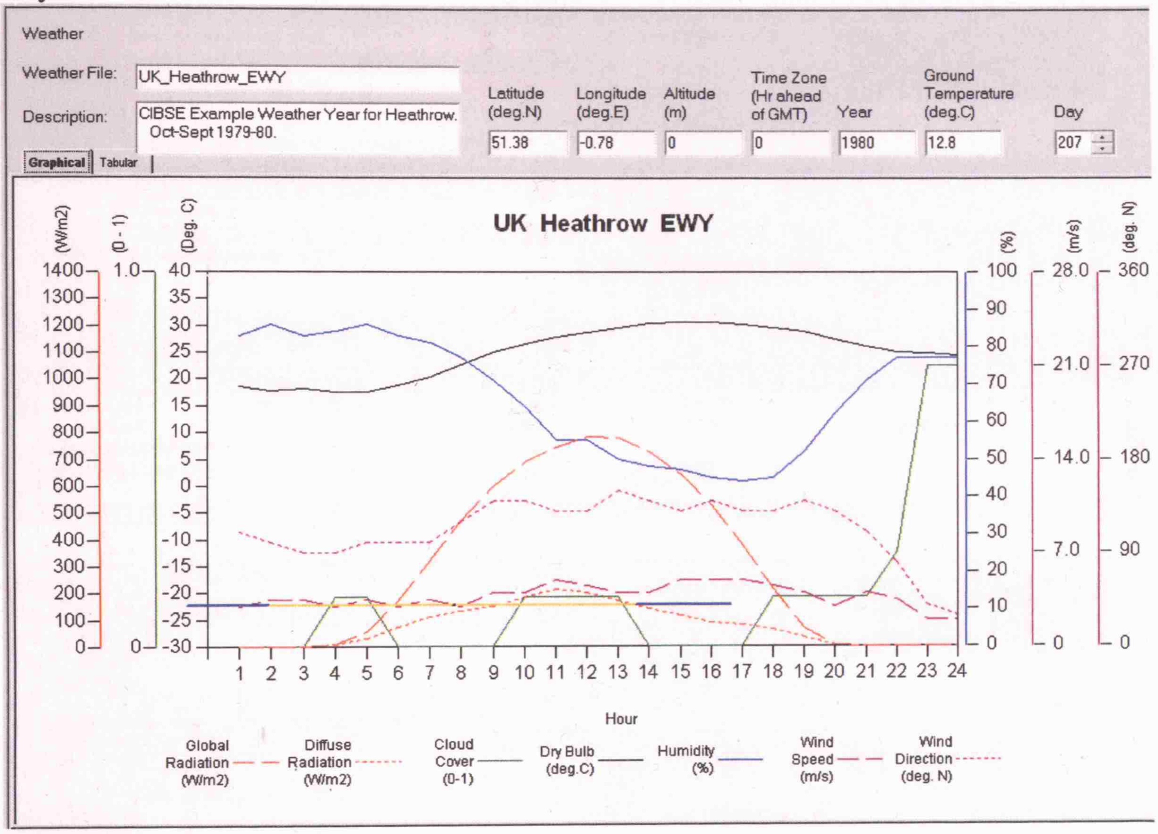
$= 8.95$ mm/d

$= 0.3729$ mm/h

Base weather
Day 1



Day 207


Weather
Weather File: UK_Heathrow_EWY
Description: CIBSE Example Weather Year for Heathrow. Oct-Sept 1979-80.
Latitude (deg.N) 51.38
Longitude (deg.E) -0.78
Altitude (m) 0
Time Zone (Hr ahead of GMT) 0
Year 1980
Ground Temperature (deg.C) 12.8
Day 207
Graphical
Tabular
UK Heathrow EWY
(W/m2)
(0 - 1)
(Deg. C)
(%)
(m/s)
(deg. N)
Hour
Global Radiation (W/m2)
Diffuse Radiation (W/m2)
Cloud Cover (0-1)
Dry Bulb (deg.C)
Humidity (%)
Wind Speed (m/s)
Wind Direction (deg. N)

Internal conditions

Name: Basic air conditioned office

Description: 8am to 6pm weekdays only

☑ Include Solar in MRT

Winter
Not Used
Summer
weekend

Internal Gain | Heating Emitter | Cooling Emitter | **Thermostat**

Name: Office heating

Description: Heating with radiators to 20C

Proportional Control ☐

Control Range: 0.00

Gain	Units	Value	Factor	Setback Value	Schedule
Upper Limit	oC	24.00	1.00	100.00	
Lower Limit	oC	20.00	1.00	-10.00	Heating Period
Humidity Upper Limit	%	100.00	1.00	100.00	
Humidity Lower Limit	%	0.00	1.00	0.00	

Name: courtyard

Description:

☐ Include Solar in MRT

Winter
Not Used
Summer
weekend

Internal Gain | Heating Emitter | Cooling Emitter | **Thermostat**

Name: No plant

Description:

Proportional Control ☐

Control Range: 0.00

Gain	Units	Value	Factor	Setback Value	Schedule
Upper Limit	oC	100.00	1.00	100.00	
Lower Limit	oC	-10.00	1.00	-10.00	
Humidity Upper Limit	%	100.00	1.00	100.00	
Humidity Lower Limit	%	0.00	1.00	0.00	

Name: Unconditioned atrium

Description: Atrium with no heating or cooling

☑ Include Solar in MRT

Winter
Not Used
Summer
weekend

Internal Gain | Heating Emitter | Cooling Emitter | **Thermostat**

Name: No plant

Description:

Proportional Control ☐

Control Range: 0.00

Gain	Units	Value	Factor	Setback Value	Schedule
Upper Limit	oC	100.00	1.00	100.00	
Lower Limit	oC	-10.00	1.00	-10.00	
Humidity Upper Limit	%	100.00	1.00	100.00	
Humidity Lower Limit	%	0.00	1.00	0.00	

Name: Basic air conditioned office

Description: 8am to 6pm weekdays only

☑ Include Solar in MRT

Winter
Not Used
Summer
weekend

Internal Gain | Heating Emitter | Cooling Emitter | Thermostat

Name: Basic office gains 37W/m2 total

Description: Basic office weekdays only

Radiant Proportion	
Lighting	0.30
Occupant	0.20
Equipment	0.10

View Coefficient	
Lighting	0.49
Occupant	0.23
Equipment	0.37

Gain	Units	Value	Factor	Setback Value	Schedule
Infiltration	ach	0.30	1.00	0.30	Buildings B - 6
Ventilation	ach	0.00	1.00	0.00	
Lighting Gain	w/m2	12.00	1.00	0.00	Buildings B - 6
Occupancy Sensible G...	w/m2	10.00	1.00	0.00	Buildings B - 6
Occupancy Latent Gain	w/m2	5.00	1.00	0.00	Buildings B - 6
Equipment Sensible Gain	w/m2	15.00	1.00	0.00	Buildings B - 6
Equipment Latent Gain	w/m2	0.00	1.00	0.00	Buildings B - 6

Name: courtyard

Description:

☐ Include Solar in MRT

Winter
Not Used
Summer
weekend

Internal Gain | Heating Emitter | Cooling Emitter | Thermostat

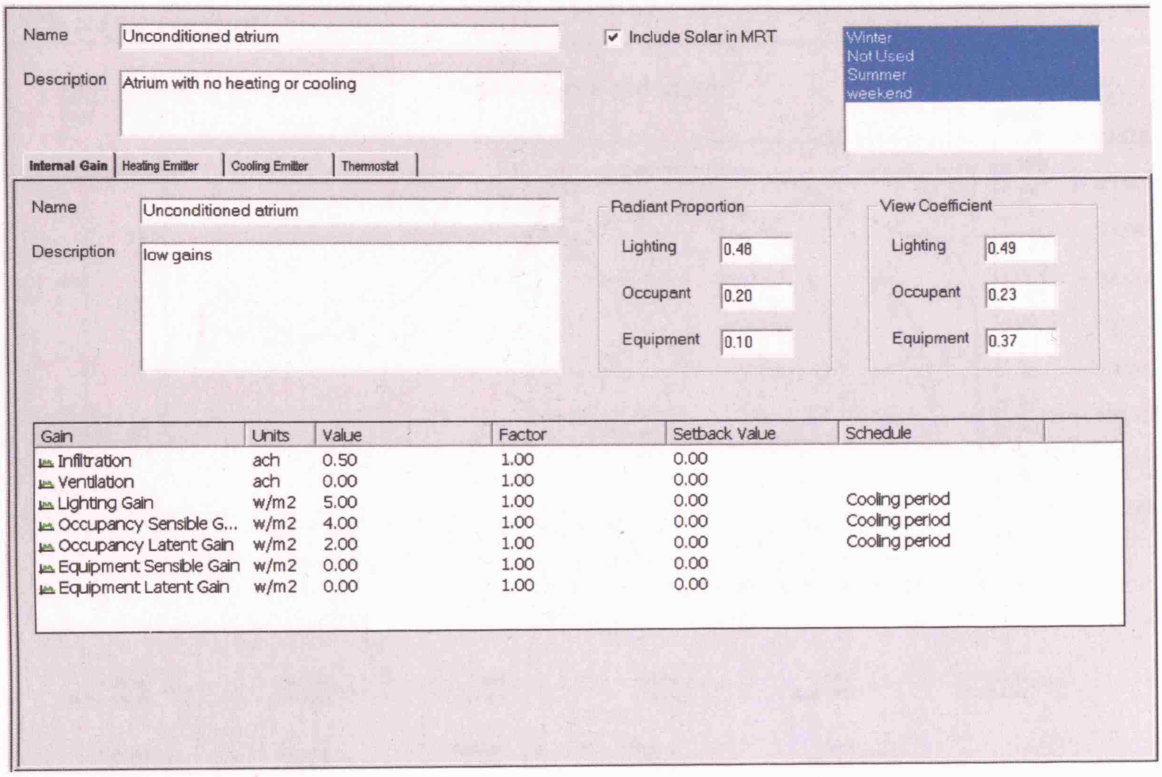
Name: Unconditioned atrium

Description: low gains

Radiant Proportion	
Lighting	0.48
Occupant	0.20
Equipment	0.10

View Coefficient	
Lighting	0.49
Occupant	0.23
Equipment	0.37

Gain	Units	Value	Factor	Setback Value	Schedule
Infiltration	ach	0.50	1.00	0.00	
Ventilation	ach	0.00	1.00	0.00	
Lighting Gain	w/m2	5.00	1.00	0.00	Cooling period
Occupancy Sensible G...	w/m2	4.00	1.00	0.00	Cooling period
Occupancy Latent Gain	w/m2	2.00	1.00	0.00	Cooling period
Equipment Sensible Gain	w/m2	0.00	1.00	0.00	
Equipment Latent Gain	w/m2	0.00	1.00	0.00	



Name: Unconditioned atrium

Description: Atrium with no heating or cooling

☑ Include Solar in MRT

Winter
Not Used
Summer
weekend

Internal Gain | Heating Emitter | Cooling Emitter | Thermostat

Name: Unconditioned atrium

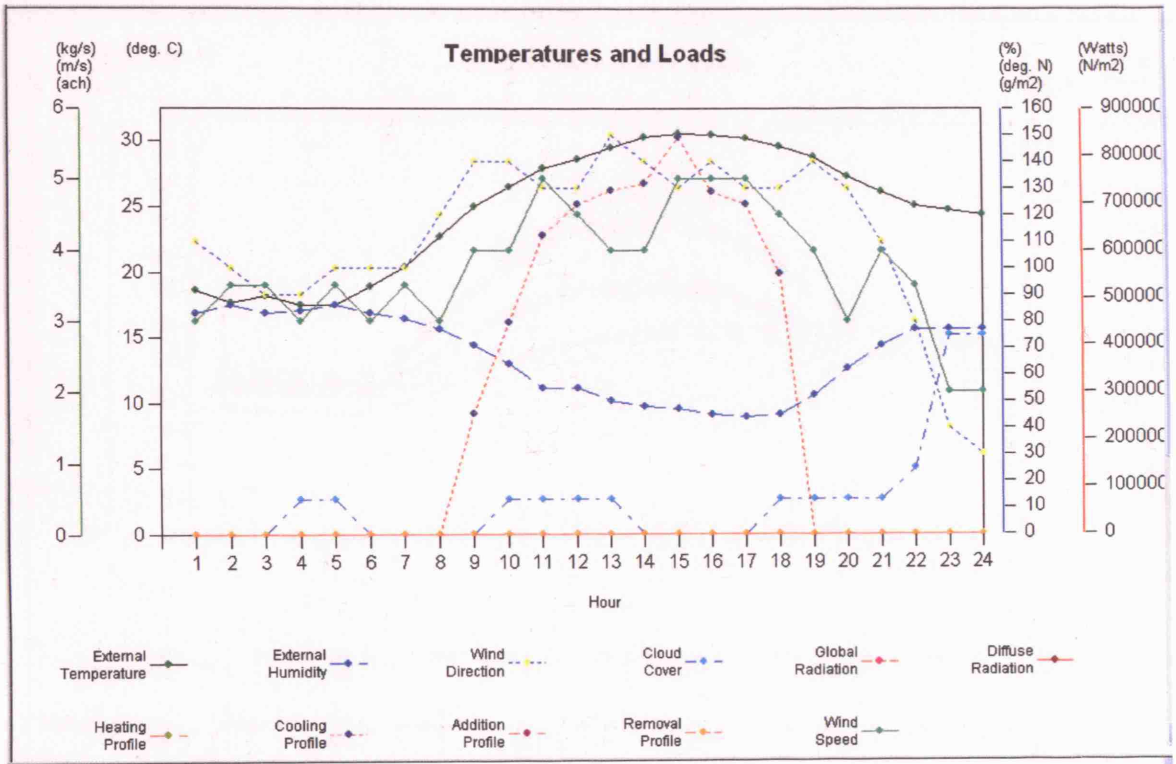
Description: low gains

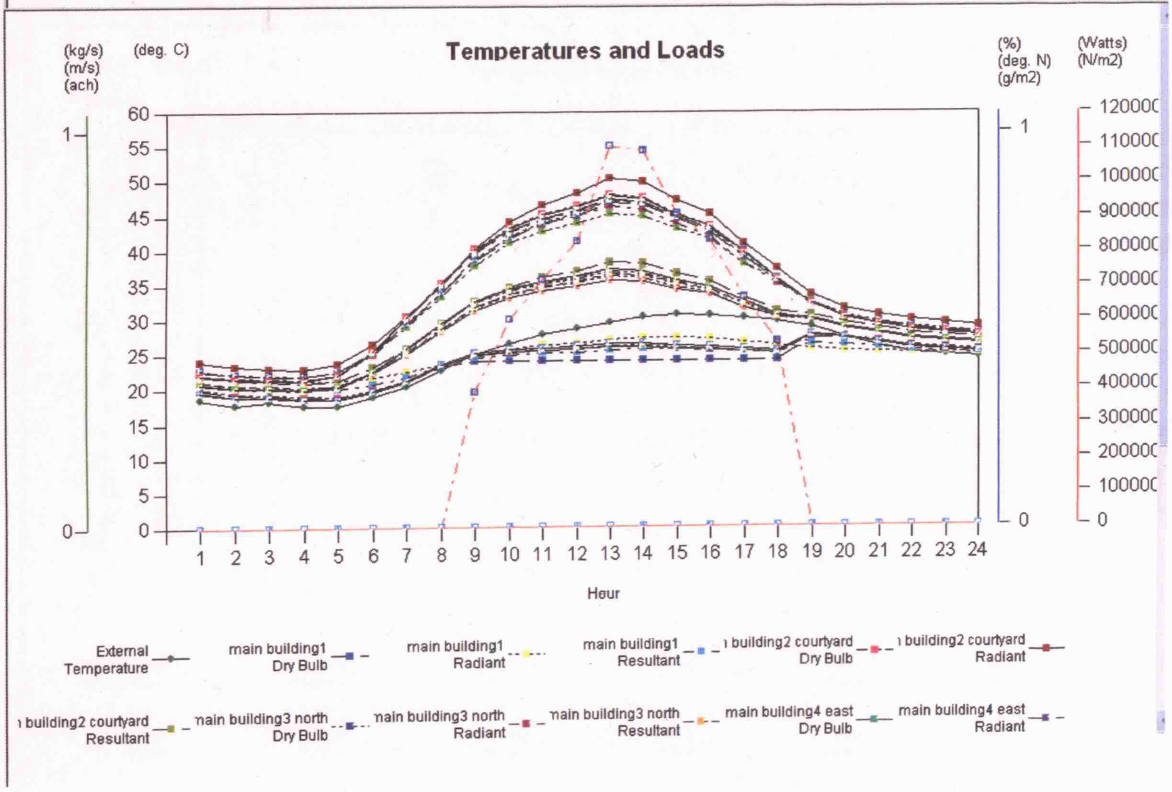
Radiant Proportion
Lighting 0.48
Occupant 0.20
Equipment 0.10

View Coefficient
Lighting 0.49
Occupant 0.23
Equipment 0.37

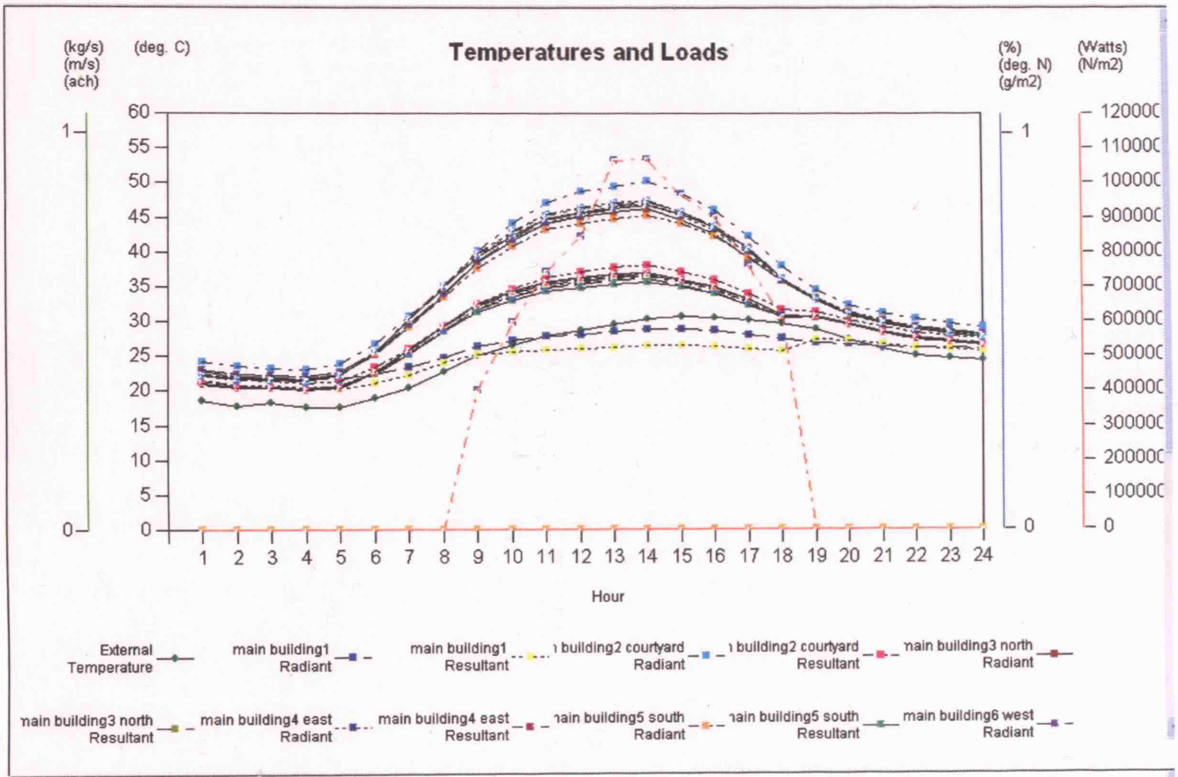
Gain	Units	Value	Factor	Setback Value	Schedule
Infiltration	ach	0.50	1.00	0.00	
Ventilation	ach	0.00	1.00	0.00	
Lighting Gain	w/m2	5.00	1.00	0.00	Cooling period
Occupancy Sensible G...	w/m2	4.00	1.00	0.00	Cooling period
Occupancy Latent Gain	w/m2	2.00	1.00	0.00	Cooling period
Equipment Sensible Gain	w/m2	0.00	1.00	0.00	
Equipment Latent Gain	w/m2	0.00	1.00	0.00	

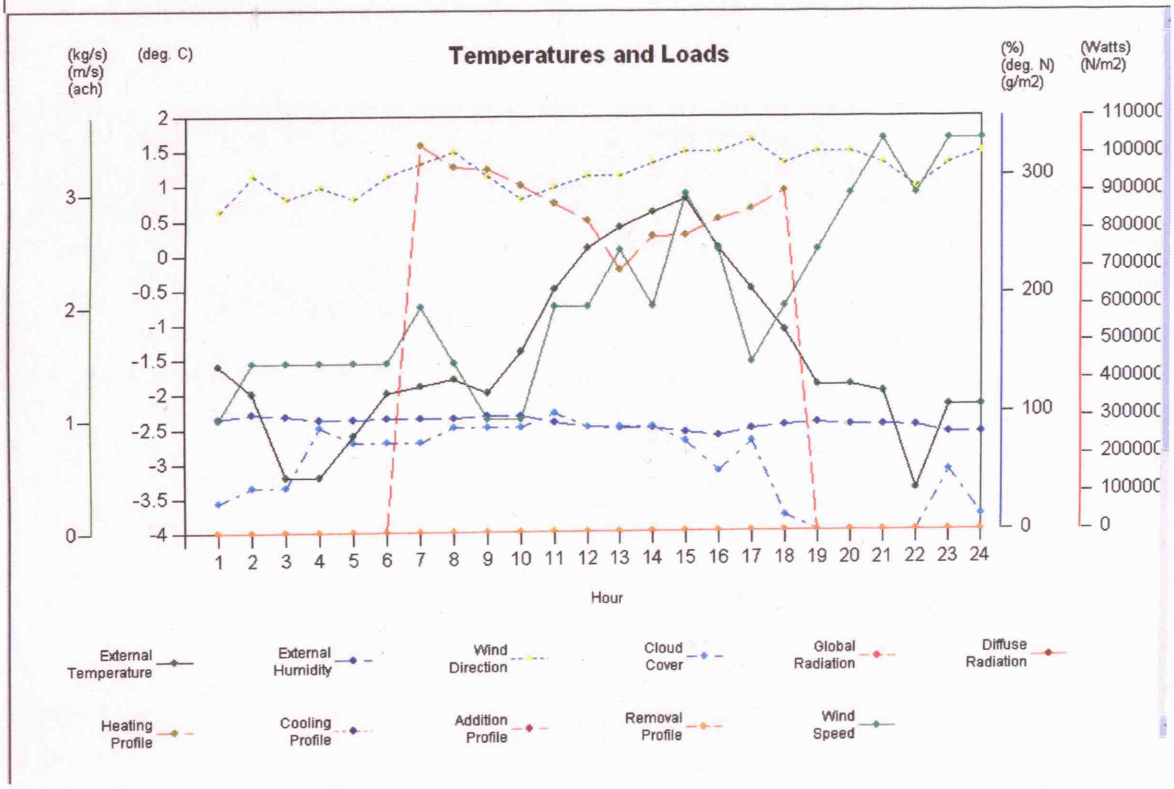
90% reflective roof



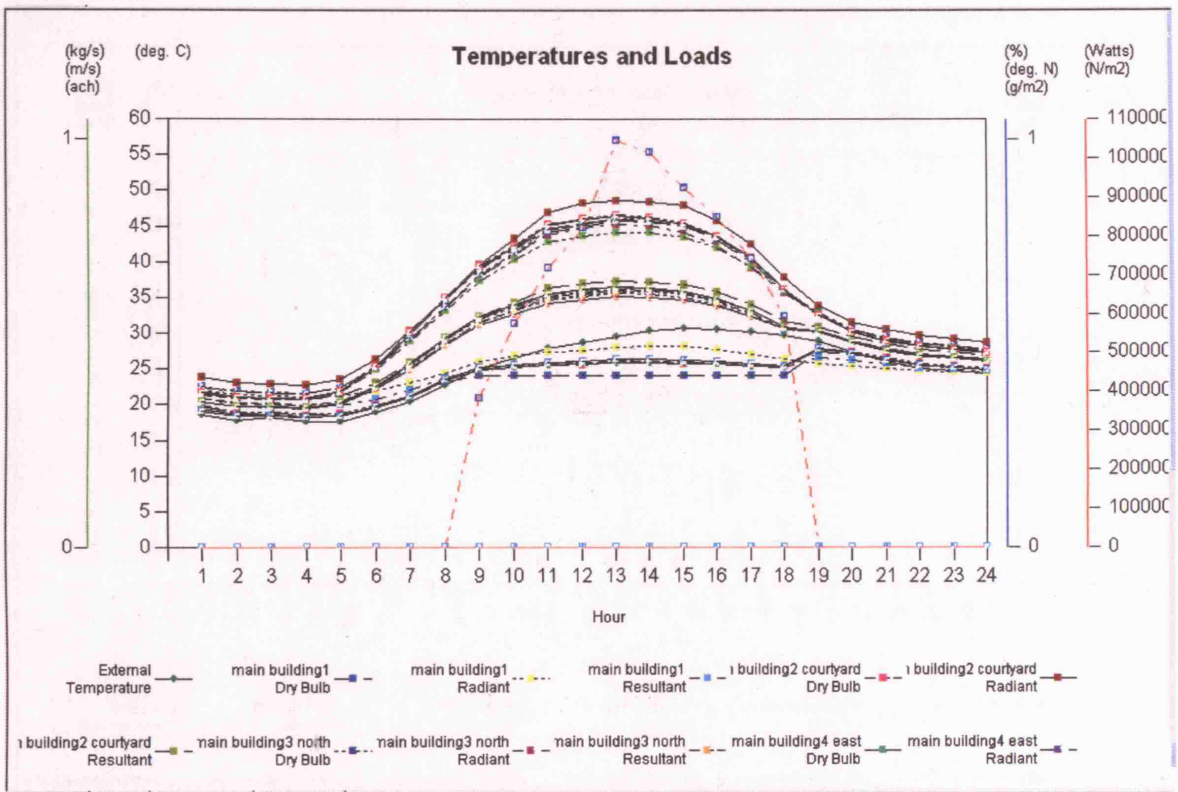


70% reflective roof

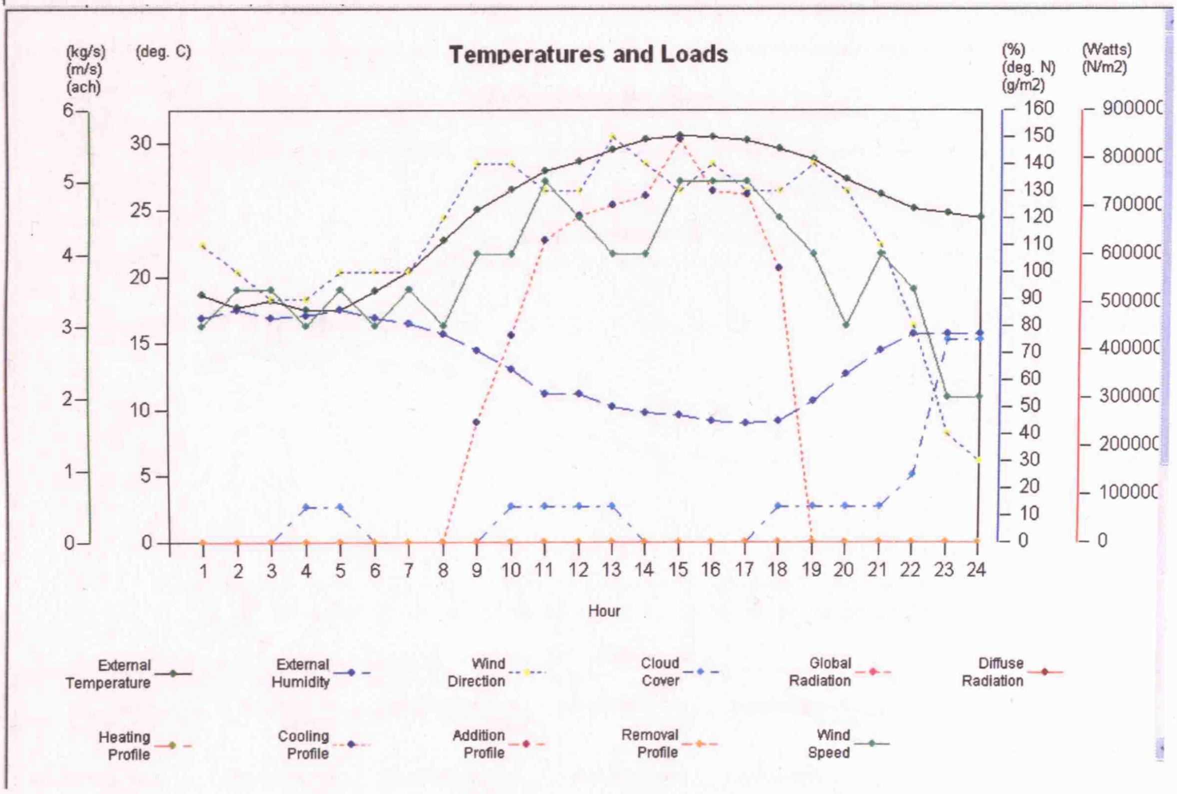




Green roof

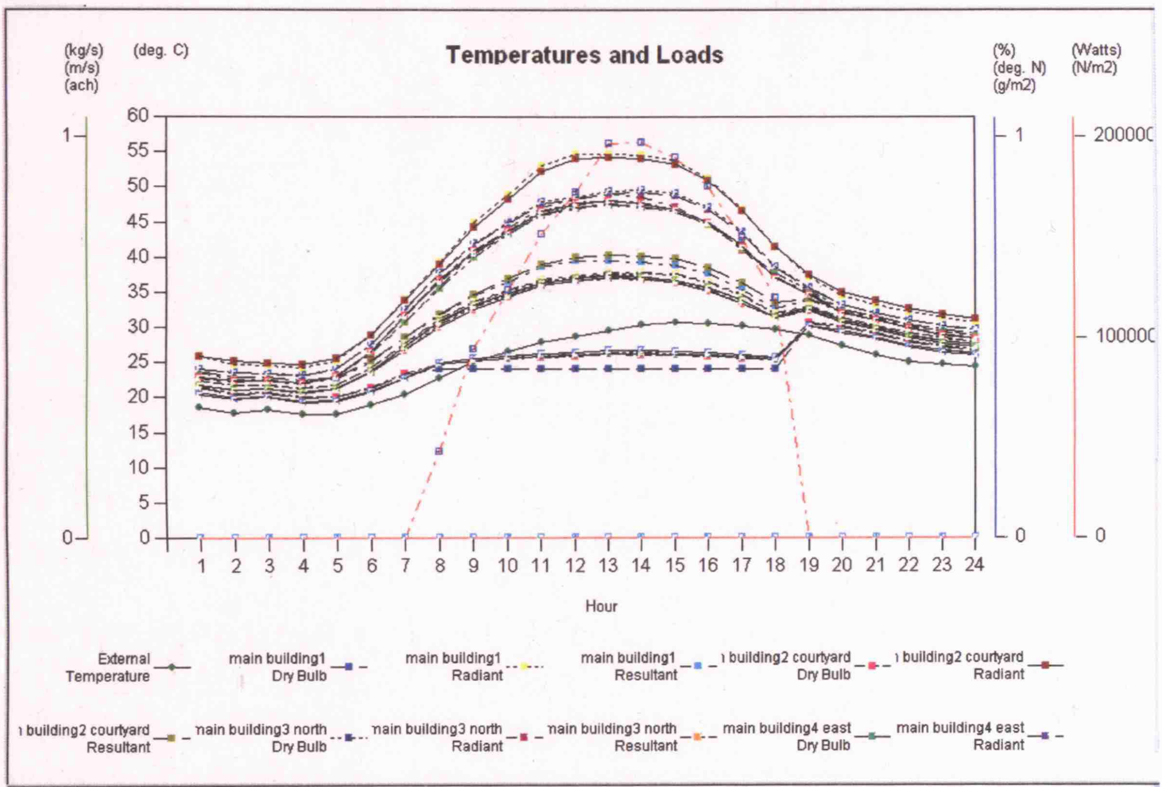


Temperatures and Loads
(kg/s)
(m/s)
(ach)
(deg. C)
(%)
(deg. N)
(g/m2)
(Watts)
(N/m2)
Hour
External Temperature
main building1 Dry Bulb
main building1 Radiant
main building1 Resultant
building2 courtyard Dry Bulb
building2 courtyard Radiant
building2 courtyard Resultant
main building3 north Dry Bulb
main building3 north Radiant
main building3 north Resultant
main building4 east Dry Bulb
main building4 east Radiant

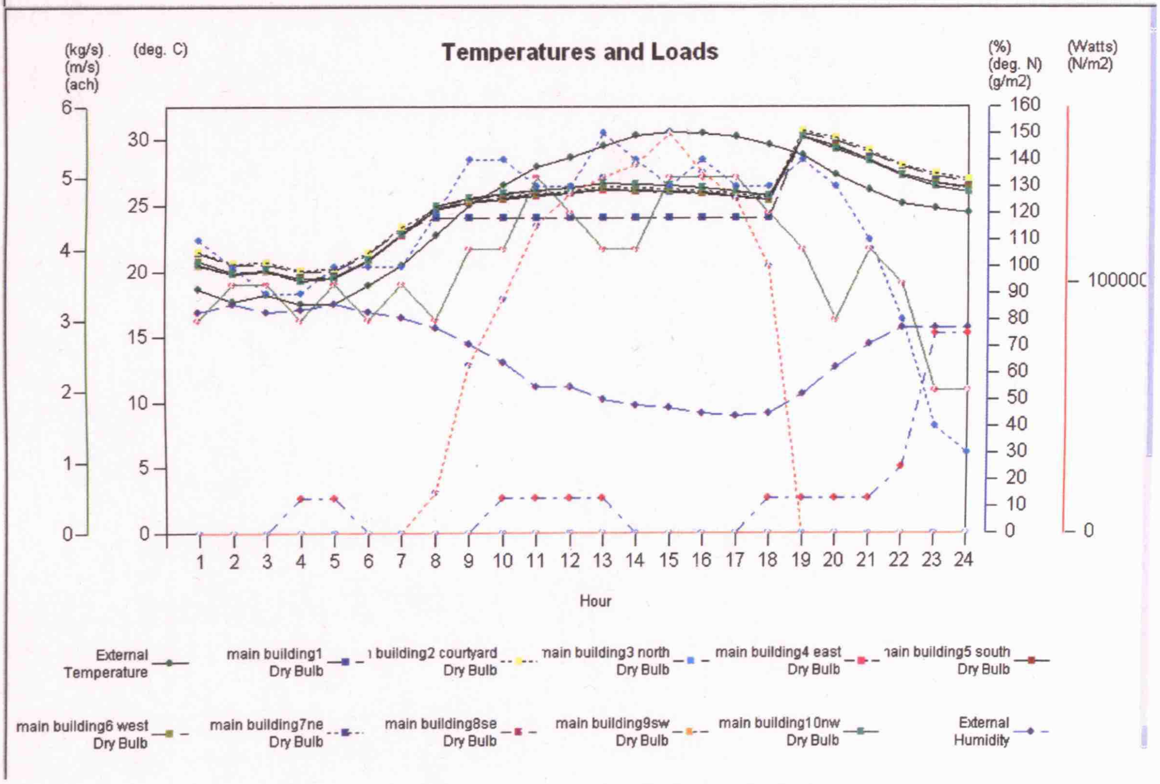


Temperatures and Loads
(kg/s)
(m/s)
(ach)
(deg. C)
(%)
(deg. N)
(g/m2)
(Watts)
(N/m2)
Hour
External Temperature
External Humidity
Wind Direction
Cloud Cover
Global Radiation
Diffuse Radiation
Heating Profile
Cooling Profile
Addition Profile
Removal Profile
Wind Speed

Base



Temperatures and Loads
(kg/s)
(m/s)
(ach)
(deg. C)
(%)
(deg. N)
(g/m2)
(Watts)
(N/m2)
Hour
External Temperature
main building1 Dry Bulb
main building1 Radiant
main building1 Resultant
building2 courtyard Dry Bulb
building2 courtyard Radiant
building2 courtyard Resultant
main building3 north Dry Bulb
main building3 north Radiant
main building3 north Resultant
main building4 east Dry Bulb
main building4 east Radiant



Temperatures and Loads
(kg/s)
(m/s)
(ach)
(deg. C)
(%)
(deg. N)
(g/m2)
(Watts)
(N/m2)
Hour
External Temperature
main building1 Dry Bulb
building2 courtyard Dry Bulb
main building3 north Dry Bulb
main building4 east Dry Bulb
main building5 south Dry Bulb
main building6 west Dry Bulb
main building7ne Dry Bulb
main building8se Dry Bulb
main building9sw Dry Bulb
main building10nw Dry Bulb
External Humidity